Nucleosynthesis during the Early History of the Solar System*

William A. Fowler, Jesse L. Greenstein and Fred Hoyle

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And the Lord shewed signs and wonders . . .
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Summary

Abundances in terrestrial and meteoritic matter indicate that the synthesis of D^2, Li^6, Li^7, Be^9, B^{10} and B^{11} and possibly C^{13} and N^{15} occurred during an intermediate stage in the early history of the solar system. In this intermediate stage, the planetary material had become largely separated, but not completely, from the hydrogen which was the main constituent of primitive solar material. Appropriate physical conditions were satisfied by solid planetesimals of dimensions from 1 to 50 metres consisting of silicates and oxides of the metals embedded in an icy matrix. The synthesis occurred through spallation and neutron reactions simultaneously induced in the outer layers of the planetesimals by the bombardment of high energy charged particles, mostly protons, accelerated in magnetic flares at the surface of the condensing Sun. The total particle energy was approximately 10^{45} ergs while the average energy was close to 500 MeV per nucleon. Recent studies of the abundance of lithium in young T Tauri stars serve as the primary astronomical evidence for this point of view. The observed abundances of lithium and beryllium in the surface of the Sun are discussed in terms of the astronomical and nuclear considerations brought forward.

The isotope ratios $D^2/H^1 = 1{\cdot}5 \times 10^{-4}$, $Li^6/Li^7 = 0{\cdot}08$, and $B^{10}/B^{11} = 0{\cdot}23$ are the basic data leading to the requirement that 10 per cent of terrestrial–meteoritic material was irradiated with a thermal neutron flux of 10^7 $n/\mathrm{cm}^2\mathrm{s}$ for an interval of 10^7 years. The importance of the (n, α) reactions on Li^6 and B^{10} is indicated by the relatively low abundances of these two nuclei. It is shown that the neutron flux was sufficient to produce the radioactive Pd^{107} and I^{129} necessary to account for the radiogenic Ag^{107} and Xe^{129} anomalies recently observed in meteorites. The short time interval, $\sim 6 \times 10^7$ years, required for the radioactive decays to be effective applies to the interval between the end of nucleosynthesis in the solar system and the termination of fractionation processes in the parent bodies of the meteorites. It is not necessary to postulate a short time interval between the last event of galactic nucleosynthesis and the formation of large, solid bodies in the solar nebula.

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PART I. INTRODUCTION

It has long been realized that severe difficulties stand in the way of any theory of the origin of deuterons* and the isotopes of lithium, beryllium, and boron in terms of thermonuclear reactions in the interiors of stars. These difficulties led Fowler, Burbidge & Burbidge (1955) to suggest that DLiBeB arise in nuclear reactions of a non-thermonuclear character at stellar surfaces and not through reactions in stellar interiors.

Since this early theoretical investigation, observational evidence has accumulated which leads to more detailed knowledge of the type of magnetic variable stars on which such surface activity occurs, and of the period in their evolution during which stars of the appropriate type experience such activity. The work of Bonsack & Greenstein (1960) and of Bonsack (1961a, b) on the abundance of Li in T Tauri stars and of Be in peculiar A stars has been particularly enlightening. The observations were interpreted to indicate that: (a) LiBeB may be formed in nuclear reactions induced by high energy particles accelerated electromagnetically in or near the surfaces of newly formed stars; (b) the degree of magnetic activity varies from star to star and the amount of LiBeB produced varies similarly; and (c) the uniformly high abundance of these elements in the T Tauri stars is the result of a correlation between flare activity and the appearance of recognizable T Tauri-like spectral features; contracting stars with little flare activity do not make large quantities of the lightest metals, do not show the erratic light variation and are therefore not T Tauri stars. On this basis, Bonsack and Greenstein suggest that the LiBeB observed in the terrestrial and meteoritic matter of the solar system were produced in early stages of the system when magnetic and nuclear activity were high. The variability in the lithium abundance observed from star to star may be connected with both the initial abundances, and its thermonuclear destruction by convective mixing in stellar interiors. The observed abundances of these light metals in terrestrial and meteoritic matter are comparable to the maximum observed in active or once active stars. Hayakawa (1960) has extended the argument to the origin of deuterons in terrestrial and meteoritic matter.

Gold (1960) has emphasized the importance of one aspect of the work of Bonsack and Greenstein—namely that they find at least ten times more Li per gram of material in the surfaces of T Tauri stars than in the surrounding nebular material. This nebula may be thought of as material remaining after the formation of the star, but because of the very large scale and large mass involved, it is not likely to be contaminated with material ejected from the star after magnetic and nuclear activity in the star's surface. On the other hand, Gold points out that the solar system is a much smaller scale phenomenon and that the planets, meteorites, and other objects in the system, could well have formed from material which had been through the Sun's surface activity and had been ejected as the Sun lost its primordial magnetic and rotational energy to the ejected material.

Although the general point of view of the present paper agrees closely with those of the authors just mentioned, we have felt the need for a more detailed

* The reader will note that reference is made to *nuclei*, not nuclides nor atoms; nucleosynthesis primarily involves nuclear not atomic processes. The word *isotope* is taken to refer to a nucleus, not an atom. Throughout the paper the symbols HDLiBeB, etc., designate nuclei, not atoms, except where indicated otherwise or where they obviously appear in molecular formulae. In listing a number of nuclei we omit commas and the word *and*.

understanding of many astrophysical and nuclear points. As an example, the production of Li through high-energy spallation reactions must lead to the two lithium isotopes being generated in closely comparable quantities. Yet the terrestrial Li^6/Li^7 ratio is 0·08. A similar situation exists for the isotopes of boron: B^{10}/B^{11} is 0·23.

These simple facts show that the nuclear situation at the surface of the primitive Sun, and within the planetary material, cannot be described wholly by a production of high-energy particles in electromagnetic processes, and spallation by such particles. Spallation reactions give lithium and boron isotope ratios of order unity. Other reactions must have played a crucial role in the determination of isotope abundances. In our opinion, the key to the situation lies in the large thermal cross-sections of $Li^6(n, \alpha)T^3$, and of $B^{10}(n, \alpha)Li^7$. These exothermic reactions possess precisely the required properties, depleting Li^6B^{10} and augmenting Li^7.

The existence of neutrons occasions no surprise in itself, for the spallation reactions themselves produce neutrons. It is the thermalization requirement that sets the intriguing problem. Why were the thermal neutrons not captured entirely by hydrogen? To understand this, and other similarly pointed questions, we have found it useful to think in terms of a definite model for the process of origin of the planetary system. This model follows the lines suggested by Hoyle (1960). We will first summarize the essential features of the model in Part II on "Preliminary Astrophysical Considerations". This will be followed by Part III on "Nuclear Considerations", by Part IV on "Further Astrophysical Considerations", and finally by Part V which constitutes the "Summary of Conclusions".

Because of the length and somewhat discursive nature of this paper the general reader may wish to turn directly to Part V. There, we have attempted to place in close juxtaposition the basic assumptions and ultimate inferences of our studies. As an alternative, the general lines of our argument can be followed without detours into side issues by omitting Sections II, 4–7 and III, 1, 11–15. On the other hand, the geophysicist interested primarily in anomalous abundances in meteorites may find reading of Sections III, 13–15 sufficient for his purposes. The attention of those interested in the nuclear composition of the cosmic rays or of intermediate energy spallation products is called to Sections III, 6 and 7 while that of biologists is called to the final paragraph of Section IV, 1. Finally, an Appendix has been provided for the nuclear physicist interested in details and alternatives in the nuclear considerations.

Before continuing, we wish to state that the nuclear and astrophysical considerations brought forward in this paper reveal an early history for the solar system, similar in some, but not all ways, to that depicted on the basis of chemical and geophysical grounds by Harold Clayton Urey. Professor Urey has written a memorable series of books and articles on the problem of the origin of the solar system. The reader is referred in particular to *The Planets* (Urey 1952) and to *Boundary Conditions for Theories of the Origin of the Solar System* (Urey 1957) which contains an excellent bibliography. We take full responsibility for our own point of view concerning nuclear and astrophysical boundary conditions and ground rules, but must acknowledge at this point, rather than later, the many contributions made by Professor Urey in this general field of investigation. Professor Urey (1960) has shown that certain conditions which follow from the discussion of the present paper are not inconsistent with his own most recent model for the early solar system.

PART II. PRELIMINARY ASTROPHYSICAL CONSIDERATIONS

1. The early solar system

The model of the early solar system used in this paper is taken to have the following properties:

(i) An equatorial disk of planetary material became detached from the primitive Sun when the radius of the system was about 3×10^{12}cm $\approx 40R_{\odot}$.

(ii) The mass of the disk was about $10^{-2}M_{\odot}$ or $\sim 10^{3}$ times the mass of the terrestrial planets. The chemical composition of the planetary disk was initially solar.

(iii) The Sun was spinning rapidly at this early stage.

(iv) A torque coupling of a magnetic character became established between the solar condensation and the planetary disk, the magnetic intensity at the Sun being not less than about 1 gauss. The torque coupling transferred angular momentum from the more rapidly rotating Sun to the less rapidly rotating disk. In spite of the low temperature, a sufficiently high level of ionization was maintained to retain the linkage between the magnetic field and the gas.

(v) Because of the comparatively small mass of the disk, in order to take up the solar angular momentum it was necessary for the bulk of the material of the disk to move very far away from the Sun, in fact to a distance of order 3×10^{14} cm in the vicinity of Uranus and Neptune.

(vi) Solid particles condensed from the initially gaseous planetary material as it moved outwards. The first particles to condense were those of low saturation pressure, notably iron and other metals, followed closely by silicon and similar elements, either pure or chemically compounded. At a later stage of the gaseous outflow, substances of significantly higher saturation pressures also condensed, notably ice and ammonia, and perhaps methane. Water ice condensed in the region of the terrestrial planets, ammonia in the region of Jupiter and Saturn. The terrestrial planets accreted in a region devoid of hydrogen and helium. On the other hand, Jupiter and Saturn accumulated large quantities of these gases.

(vii) Particles that grew to a diameter of at least one metre were left behind by the outflowing gas. We refer to these as "metric" planetesimals or just planetisimals throughout the remainder of this paper. The circumstance that solids were left behind, in this way, produced the gross features of the chemical segregation necessary for an understanding of the origin of the terrestrial planets. Three critical features of the terrestrial planets become readily understandable: they lie on the inside of the planetary system; they are composed very largely of materials of low saturation pressures—rocks and metals—and their masses are small. The last feature arises because the concentration of MgSiFe in the original material was only about 10^{-3} by mass. In view of (ii), the total mass of the materials of low saturation pressure was thus of order $10^{-5}M_{\odot}$; this is just the order of the total mass of terrestrial planets.

(viii) Solar gravity at the periphery of the planetary system was so weak that the very light gases, hydrogen and helium, largely evaporated into interstellar space. The outer pair of great planets, Uranus and Neptune, consequently contain relatively little hydrogen and helium.

To these features of the astrophysical model, we now add the following specific points that will be made explicit use of in later sections of the present paper.

2. The luminosity of the Sun

The temperature within the planetary material is required, both for estimating thermal neutron cross-sections and for determining saturation vapour pressures. Of these, the saturation pressures are the more critical, since they depend on exponentials, as compared with a $1/v$ law for the neutron cross sections.

To estimate the temperature within the planetary material, at a distance of 1 AU, we need the luminosity of the primitive solar condensation. The situation is complicated by the requirement that the luminosity be given at the critical phase in the relation of the Sun to the planetary disk during the main outflow of planetary gas. This corresponds to the stage at which the torque coupling carried across the main supply of angular momentum from the Sun to the disk, namely when the radius of the solar condensation was of order 3×10^{12} cm—long before the Sun reached the main-sequence, and long before the observable stages of known contracting stars.

Schwarzchild (1958) points out that the luminosity–radius relation during evolution in early contracting phases computed by Henyey, Le Levier & Levee (1955) can be represented approximately by $LR^{0\cdot78}$ = constant. This corresponds to a modified Kramers law in which the variation in the correction term $t/\bar{g}$, is included in the density term in the factor as $\rho^{1-\alpha}$, with $\alpha = 0\cdot09$. In an otherwise homologous sequence, $\rho \approx R^{-3}$, so the opacity correction is $R^{3\alpha}$. At the first point computed by Henyey & others, for $M = 1 M_{\odot}$, we find $R = 3R_{\odot}$; from here the opacity change until the main sequence is reached is only $\Delta \log \kappa = 0\cdot27 \times \log R = 0\cdot27 \times 0\cdot48 = 0\cdot13$ (about 35 per cent). Thus the major part of the change of $t/\bar{g}$ from its main sequence value (4 to 6 in normal stars) to unity is still to be encountered as R increases towards earlier evolutionary stages. The modified homology law, $LR^{0\cdot78}$, if valid as far as $R = 2 \times 10^{12}$ cm (30 $R_{\odot}$), when we start from Henyey's point $L = 3 \times 10^{33}\,\mathrm{erg\,s^{-1}}$ ($R = 3\,R_{\odot}$), gives $L = 5 \times 10^{32}\,\mathrm{erg\,s^{-1}}$. This value corresponds to a correction to the opacity of $0\cdot28 \Delta \log R = 0\cdot28$, or a total correction $\Delta \log t/\bar{g}$ of $0\cdot41$. Since $\bar{T}$ and $\bar{\rho}$ for these early stages are very low, $t \approx 1$, and we are apparently safe in extrapolating the $LR^{0\cdot78}$ at least as far as 40 $R_{\odot}$. The bolometric magnitude derived is about $+7\cdot2$ and the effective surface temperature is near 500°K. The luminosity that we give for this early stage of the Sun is not excessively low; Cox & Brownlee (1960) (unpublished) give $M_b \approx +9$ at $T_e = 500$°K (for an even smaller radius). Straightforward homology transformation from the initial main sequence luminosity back to 30 $R_{\odot}$ can be made using interpolation in the Keller–Meyerott opacity tables. The result is $L = 1\cdot7 \times 10^{32}\,\mathrm{erg\,s^{-1}}$. If radiative opacity still dominates throughout, this is almost certainly a lower limit (bolometric luminosity $\approx +9$). Secondary effects might be decisive in the opacity in the outer layers, e.g. negative ions or metallic dust grains. It is interesting to note that the relative concentration of H^- is quite large at the centre of such a star—(10^{-7} of total H, 10^{-4} of neutral H)—but fortunately not large enough to affect the opacity at the centre.

From the luminosity L in $\mathrm{erg\,s^{-1}}$, the temperature near the primitive Sun can be computed. On the assumption of direct, unobscured solar illumination, the temperature of a rotating spherical, black-body is 170°K at one astronomical unit from the Sun, or, in general:

$$T = \frac{170}{r^{\frac{1}{2}}}\left(\frac{L}{5 \times 10^{32}}\right)^{\frac{1}{4}} {}^{\circ}\mathrm{K}. \qquad (1)$$

At the lowest plausible value of $L = 1{\cdot}7 \times 10^{32}$, we find $T = 130°/r^{\frac{1}{2}}$. The gas and dust in the nebula partly absorbs and partly diffuses the radiation. In case of conservative scattering and optical depth to the Sun near unity, the spherical particle will be completely illuminated rather than only on its sunward side. Under this circumstance, the black-body temperature is raised by $2^{\frac{1}{2}}$, or to the range 150° to 200°K. The plausible temperature range, 130° to 200°K, at 1 AU has an additional change with distance, i.e. from Mercury to Mars as $1/r^{\frac{1}{2}}$, an additional factor of 2. We are faced, therefore, with temperature conditions that are variable, slightly with $L^{\frac{1}{4}}$, more steeply with $r^{\frac{1}{2}}$, and depend on the efficiency of diffusion of light by the gas and solids. However, it is apparent that even with low vapour pressure, an icy matrix will be the stable form of water, near the Earth, for a long period at the critical phase in the contracting stage. Only at Mars or beyond would solid ammonia (freezing point 195°K) become important, so that from Venus to Mars, among the components of astrophysically abundant light elements, ice would dominate. However, these freezing bodies would also contain MgAlSi and the common metals, in various compounds, or in atomic form if insufficient activation energy were available.

3. The time scale

The Kelvin–Helmholtz contraction time to radius R for solar condensation must be of the order $3 \times 10^7\,(R_0/R)^{\frac{1}{4}}$ years, where R_0 is the radius at the zero-age main-sequence. Above, in Section II, 1, we have already remarked that during the initial stages of the outflow of planetary gas $(R/R_0)^{\frac{1}{4}} \approx 6$. The time scale for the outflow is thus $\approx 5 \times 10^6$ years $= 1{\cdot}5 \times 10^{14}$ s, the value given by Hoyle (1960).

Now, while this estimate must certainly be of the correct order of magnitude, a more precise value would presumably be longer, since the effect of rotation must tend to slow contraction. An increase of time scale to $\approx 10^7$ years $= 3 \times 10^{14}$ s, does not therefore seem unreasonable. Later considerations, of a nuclear character, give support to this detail. The time scale for the growth of the first large bodies in the planetary disk may be appreciably shorter.

4. Level of ionization maintained by ionizing radiation

If the gas contains relatively young nuclear species with rapid radioactive disintegrations or if it is bombarded by high-energy protons a certain low level of ionization is maintained. The particle or gamma radiation is completely stopped in the gas and produces an energy input available in the form of an electron–ion pair for each 30 eV. The recombination of these ions can be computed by summing the captures on all levels of atomic hydrogen and yields:

$$E = 5{\cdot}7 \times 10^{-22} \frac{n_i n_e}{T^{\frac{1}{2}}} \text{ erg cm}^{-3}\text{ s}^{-1}. \tag{2}$$

Much of this is in Lyman continuum, which could be used many times to re-ionize the hydrogen. If the level of ionization is low, then the number of charged particles in terms of the gas density, ρ, is:

$$n_i = n_e = \frac{x\rho}{m_H}, \tag{3}$$

where x = fraction of hydrogen ionized. Thus:

$$E = \frac{x^2\rho^2}{T^{\frac{1}{2}}} 2 \times 10^{26} \text{ erg cm}^{-3} \text{ s}^{-1}. \tag{2'}$$

If the high-energy input is also E, then the steady-state level of ionization, x, is obtained:

$$x = \frac{T^{\frac{1}{4}}E^{\frac{1}{2}}}{\rho} 7{\cdot}1 \times 10^{-14}. \tag{4}$$

Consider that a total of 10^{45} ergs of high-energy protons and about the same amount of ultraviolet flare-radiation is to be dissipated in the contraction time, 10^7 years. If this radiation is uniformly spread through a cylinder of 10^{39} cm^3 (as far as Mars, but in a flattened discoidal volume), $E = 7 \times 10^{-9}$ erg cm^{-3} s^{-1}. The kinetic temperature governing recombination will be much higher than the black-body temperature. Normally, for hydrogen, either $T = 10^2$ or $T = 10^4$ °K. Then $2 \times 10^{-17}/\rho < x < 6 \times 10^{-17}/\rho$. When or where ρ is small, the ionization is, on the average, enough to insure high conductivity. When $\rho > 10^{-9}$, $x < 10^{-7}$, and the conditions for maintaining the torque coupling between magnetic field and gas are violated (see Hoyle 1960, p. 44). It is interesting to note that the high-energy proton flux is, on the average, able to maintain the proper level of ionization until the volume of the nebula containing the inner planets has shrunk to 10^{39} cm^3. Obviously, the density, the charged-particle flux, and therefore the level of ionization are violently variable, in space and time.

This level of ionization suggests that chemical combinations could occur in spite of the low temperature. Radiative captures of ions, or three-body collisions involving ions are possible because of the relatively high density. Normally either H^+ or H^-, and the initially abundant atomic CNO would be involved, as well as oxidation of the metallic constituents. The probability of ionization or dissociation is low.

5. Coagulation of particles

A simple calculation shows that for $R \approx 3 \times 10^{12}$ cm, and for a luminosity of ≈ 2 to 5×10^{32} erg s^{-1}, the surface temperature of the primitive solar condensation did not exceed 500 °K. At this low temperature, all typical low saturation pressure materials—iron and oxidized silicates—would already be condensed in solid form.

It therefore seems possible that small solid particles already existed near the primeval Sun at the time the planetary gases became separated from the Sun. Indeed, a small fraction of the original grains, present in the interstellar gas cloud from which the solar system condensed, may have survived near the solar surface itself. Such particles are known to possess a wide range of sizes up to at least 3×10^{-5} cm.

After separation from the Sun, and after cooling had taken place within the planetary gases, low saturation pressure materials condensed. If a sufficient fraction of the original interstellar grains still survived, the low saturation pressure materials would probably condense around the grains, rather than form new solid particles.

It is of interest to consider the size to which the surviving grains might grow. Let the number of surviving grains be a fraction f of the original total number. Then the ratio of the mass of low saturation pressure materials in the gaseous phase to that in the solid phase must be at least f^{-1}. If *all* the low saturation pressure materials were condensed in the original interstellar gas, the ratio would be f^{-1}, otherwise the ratio would be $>f^{-1}$, but probably not very much greater. Condensation onto the surviving grains therefore increases their radii by a factor of at least $f^{-\frac{1}{3}}$. Since survival of the grains is only possible in the outermost regions of the primeval Sun, we expect f^{-1} to be a large number, perhaps in the range 10^6 to 10^9. Hence, an original radius of 3×10^{-5} cm would be increased to the range 10^{-3} to 10^{-2} cm but not to metric dimensions, as is required by (vii) in Section II, 1. For an increase to metric dimensions, f^{-1} would need to be of order 10^{21}. Not only is this implausibly large, but the surviving grains would then be so few in number that the low saturation pressure materials could not all condense on the surviving grains. Instead, a separate condensation of a swarm of new tiny particles would take place.

Our expectation is that the first condensation process involving the low saturation pressure materials (mainly MgSiFe) building on residual interstellar grains, or forming new condensation nuclei increased the particle sizes to the range 10^{-3} to 10^{-2} cm, but not to metric dimensions. The question therefore arises as to how, at a later stage, bodies of metric dimensions were formed.

The answer to this critical problem appears to depend on a further condensation process, not of metals and other materials of comparatively high boiling point, but of ice. The key to the situation lies in the low temperature we derived from the low initial solar luminosity. When the gas reached a distance of 1 AU from the condensing Sun, the black-body temperature within the gas fell to 130° to 200 °K. At this temperature, ice must have formed around the solid particles. The nuclear considerations of Section III, 8 indicate that ice constituted about 35 per cent by mass of the metric bodies. Thus the ice constitutes two-thirds of the volume.

A calculation, based on the Stokes formula for the drag on a sphere moving through a gas, shows that particles of radii 10^{-3} to 10^{-2} cm would fall towards the plane of the solar system at speeds of the order 10^{-3} cm s^{-1}. In the course of this motion, the particles would encounter each other in very gentle collisions. In such collisions, particles might well remain in contact for quite a length of time—long enough for condensing ice to cement them firmly together. The space density of the particles, assuming them to be at first uniformly distributed through a disk of radius 10^{13} cm and thickness 10^{12} cm was 3×10^{-4} cm^{-3}. The mean free path between encounters was $\sim 10^8$ cm. At relative velocities of order 10^{-3} cm s^{-1}, the interval between successive encounters of an individual particle with other particles was $\sim 10^{11}$ s. This is short compared to the general time scale $\sim 3 \times 10^{14}$ s. Hence, only a moderate fraction of encounters need succeed in a cementing together of the particles. We note moreover, that as the particles sink toward the plane of the solar system, the thickness of the particle distribution decreases, the space density of particles increases, and the rate at which encounters take place rises accordingly.

The eventual size to which particles can grow by this cementing process is set by the strength of the ice. A calculation of this limiting size is difficult because of uncertainty in the precise conditions of the encounters. As the particles grow, their relative velocities presumably increase, but to what value is uncertain. It seems inherently plausible, however, that the eventual size would be set at metric dimensions. It is difficult, for example, to imagine an encounter between planetesimals greater than 100 m moving at speeds of several metres per second which results in coagulation. Rather would we expect fragmentation to take place in such a case.

6. Internal motions and the growth of larger bodies

Under any conditions the motion of the gas and of the planetesimals carried along must be largely turbulent. The velocity dispersion locally is damped by viscosity. However, we have some fossilized evidence of the amount of peculiar motion in inner zones of the nebula in the present values of the inclination and eccentricity of the planets. Jupiter almost completely determines the invariable plane of the present solar system; at the earlier phase we discuss, any systematic deviation from the plane of Jupiter's orbit is irrelevant. But now the orbital inclinations of the terrestrial planets differ by 7° and the eccentricities range from 0·007 to 0·206. Therefore, velocity vectors of large volumes of the gas must have differed from the circular velocity by about ± 5 per cent when the planets themselves began to condense, i.e. by about 1 km/s. So large a peculiar motion could not represent the internal velocity distribution, but does indicate systematic spatial differences in z-coordinate and circularity of the gas orbits. Another reflection of such motions may be found in the tilt of the Sun's plane of rotation, which differs by about 7° from the ecliptic.

The local values of random motion of the planetesimals with respect to the gas, and each other, limit their size. Thermal and Brownian motion is negligible. Viscous drag ensures that the planetesimals follow the gas very closely. For example, a differential velocity, v_p, will be damped in a short time, i.e. a solid body of radius r, and density unity, exchanges its own momentum with the gas of density ρ in a time given by:

$$\tau = \frac{4r}{3\rho v_p}. \tag{5}$$

Thus, in a year, at $\rho = 10^{-9}\,\mathrm{g\,cm^{-3}}$, if $r = 10\,\mathrm{m}$ a peculiar motion $v_p = 0{\cdot}4\,\mathrm{km/s^{-1}}$ will be damped out. The re-stirring time of the eddies will actually be longer than a year, perhaps $\approx 10^2$ years. The planetesimals might then be thought of as in Brownian motion, re-agitated by turbulent eddies. The peculiar speeds of the planetesimals then is found to be small compared to the orbital motion, perhaps less than $10^3\,\mathrm{cm\,s^{-1}}$. Once the planetesimals fall out of the gas, viscous drag becomes irrelevant.

There is a size limitation imposed by collisions between planetesimals, either by mechanical strength or radiation heating. The energy input to be dissipated after collision is proportional to the mass, i.e. r^3; the total cohesive strength is proportional to r^2, as is cooling by radiation. Consider radiation alone; assume that the total kinetic energy of a collision is uniformly spread through the solid and must be dissipated by black-body radiation at $T < T_{\mathrm{crit}}$. The combined body resulting from a collision and sticking together of two equal masses must dissipate one-half the initial v_p, i.e.

$$8\pi r^2 \sigma T^4 = \frac{4\pi r^3}{3} \times \frac{v_p{}^2}{4}. \tag{6}$$

Since $T_{\mathrm{crit}} < 273\,^{\circ}\mathrm{K}$, we find:

$$r v_p{}^2 < 8 \times 10^6\,\mathrm{cm^3\,s^{-2}}. \tag{7}$$

Thus the melting temperature is surpassed, if $v_p = 10^3 \text{ cm s}^{-1}$, for $r > 10$ cm. The ice in the larger planetesimals cannot melt instantaneously, but conditions for partial melting, sticking and partial evaporation are encountered for $r > 10$ cm. Above 10 m, mechanically fragility and partial evaporation become quite destructive influences. Mechanical fracture is the main effect at low velocities.

To sum up, icy aggregates grew to metric dimensions, at which stage the resulting planetesimals were no longer carried along by the outflowing gas, but were left moving in orbits around the Sun, at distances of order 1 AU. Individually, each planetesimal consisted of small particles, largely composed of the oxides of common metals, embedded in a matrix of ice. The role of the ice in the moderation of neutrons is the significant new feature of this picture.

7. The outer planets

It is not within the scope of the present paper to discuss the evolution of the metric planetesimals into kilometric planetoids and ultimately into planets. The structure of meteorites shows very clearly that the details of this process must have been highly complex. We only wish to remark that the time scale for the ultimate formation of planets may have been greater than the time scale (10^7 years) for the stage we consider but that the first large bodies, kilometric planetoids, in the solar system probably formed in an appreciably shorter time.

While we have no requirement in the later parts of this discussion for considerations relating to the major planets, the following points seem worth mentioning briefly. At the greater distance of Jupiter and Saturn, ammonia must have condensed from the gaseous phase. It is to be expected that the initial stages in the formation of Jupiter and Saturn possessed close analogy to the case of the terrestrial planets. Coagulated ammonia particles of metric dimensions gradually built themselves into more and more massive planetoids. Eventually, the planetoids began to acquire material through gravitation forces rather then by chance collisions. At this stage, a crucial difference developed between Jupiter and Saturn on the one hand, and the terrestrial planets on the other. In the former, the planetoids were embedded in a large quantity of gas, largely hydrogen and helium. This gas was gradually acquired by the growing Jupiter and Saturn. The terrestrial planets, on the other hand, were formed in a region largely devoid of gas; thus we explain, for example, why the Earth possesses so little neon.

The planets, Uranus and Neptune, present a somewhat different case. At the distances of these planets, and at the temperature implied by radiative flux considerations, methane and other gases must have condensed from the gaseous phase. The early stages in the formation of Uranus and Neptune may well have consisted in the gradual coagulation of particles of solid methane. The situation concerning the acquisition of gas by gravitation was intermediate between the case of the terrestrial planets and the case of the inner pair of great planets Jupiter and Saturn. The region of formation of Uranus and Neptune was not almost wholly devoid of gas as in the terrestrial planets, but the great over-abundance of hydrogen and helium present in the case of Jupiter and Saturn was absent. Neon was probably the main constituent of the gas acquired by Uranus and Neptune.

Uranus and Neptune are intermediate in their masses between the terrestrial planets and Jupiter and Saturn simply because they were intermediate in their acquisition of gas. The comets, located now at enormous distances from the Sun, may represent condensations in the out-flowing gas. On the other hand, the comets may have been ejected by dynamical encounters among the planetesimals.

8. The energy available for electromagnetic processes

The transfer of angular momentum from the Sun to the planetary material conserves angular momentum but it does not conserve energy. Only a small fraction of the initial energy of rotation of the Sun passes to the planetary material. The remainder must be dissipated. According to Hoyle (1960), the quantity of energy involved was $\sim 5 \times 10^{45}$ erg. The mechanism of torque coupling between the solar condensation and the planetary disk caused the initial energy of spin to be stored within the Sun as magnetic energy.

It is natural to appeal to the mechanism of the solar flare (Gold & Hoyle 1960) to provide for the mode of dissipation of this stored magnetic energy. A characteristic of the solar flare is that the stored energy of a magnetic field is converted into the energy of high-speed particles with a surprisingly large efficiency. On this basis, it is reasonable to take $\sim 10^{45}$ erg as the quantity of energy to be dissipated as highly accelerated particles.

Flares take place on the present day Sun at such small optical depths that outward moving accelerated particles readily escape, provided the magnetic field permits them to do so. During the origin of the solar system, the lines of magnetic force connected the solar surface to the planetary disk. Hence, outwardly emitted particles were indeed free to move along magnetic field lines through the planetary material, provided the flares occurred at small optical depths at that time.

Our picture then is of a sequence of powerful flares occurring at the condensing solar surface. Because the magnetic field lines passed directly from the solar condensation to the planetary material, accelerated particles spiralled readily outwards from the Sun to the planetary material and did not just travel radially out into space. In particular, the solid condensations were bombarded by highly energetic particles, largely high-energy protons. The total energy of this bombardment was of the order of 10^{45} erg.

9. The magnetic fields

A very delicate balance between various forces is required in the region of the terrestrial planets where the solid planetesimals were left behind by the gas. The energy requirements that will be found in the sections on nuclear reactions indicate that no large number of high-energy protons can be wasted on inelastic collisions or ionization of any free gaseous hydrogen remaining. Therefore, we must assume that the mass of gaseous constituents streaming outwards must be low compared to that of the solids, during a major portion of the time interval discussed above. But unless the interaction of the solids and the magnetic field is appreciable (a problem in magnetohydrodynamics not yet considered, a "dusty" plasma), it is the gas that must contain the magnetic field and prevent the lines of force from snapping far out of the ecliptic plane. Hoyle (1960) provided a sheet of gaseous material in the ecliptic for just this purpose. The question arises as to whether a low density of gas, and low ionization, is compatible with the magnetic fields present.

For example, consider the force on a volume of partially ionized gas, electron density N_e,

$$\frac{e\mathbf{v}\wedge\mathbf{H}}{c}N_e,$$

balanced by the radial gravitational field of the Sun, $GMNm_H/r^2$. We ignore the forces on the ions (mostly protons). The field will be constrained by gravity if

$$\frac{GMNm_H}{r^2} > \frac{e\mathbf{v}\wedge\mathbf{H}}{c} N_e. \tag{8}$$

If we replace the vectors by their magnitudes and v by the circular velocity,

$$H(r) < \frac{cm_H}{e}\frac{(GM)^{\frac{1}{2}}}{r^{\frac{1}{2}}}\frac{N}{N_e}. \tag{9}$$

Since the degree of ionization, x, is low ($N/N_e = 10^7$) we find $H(r) < 10^{-4}$ gauss.

The initial magnetic energy of 10^{45} ergs is stored almost entirely in the solar surface but $\sim 10^{37}$ ergs must be stored in the planetary disk of dimension $\sim 10^{39}$ cm^3. This corresponds to an original field of 1 gauss. Almost all of this is required to move the gas outwards and for dissipation as fast protons and ultra-violet radiation. The final solar field, approximately a dipole, of about 1 gauss gives about 10^{-3} gauss at the Earth, at a stage where the dipole length is 10 times the final solar radius. Actually, the solar field was probably largely shielded by the twisted multipole fields in the ecliptic plane, so that an effective radial component $H(r) < 10^{-4}$ gauss does not seem impossible. The field in the direction perpendicular to the ecliptic may have more serious effects, since the gravitational restoring force is small, within the gaseous disk, and approaches the radial component only at large heights. Thus a possible stable pattern is one in which the twisted lines of force bend outwards from the ecliptic, and return to it at several astronomical units.

10. Generality of the nuclear processes

In conclusion, let us stress that although we have had the above astrophysical model in mind throughout the discussion of nuclear events to follow, all essential nuclear processes stand by themselves, independent of any particular model of the origin of the planetary system. The nuclear results provide stringent constraints that must be satisfied by any satisfactory theory of the origin of the solar system. These constraints we believe to constitute the most direct and reliable evidence yet available concerning the physical conditions that existed at the time of origin of the planets. The nuclear considerations are also relevant to the possible production of DLiBeB in supernova explosions. This subject will be treated in a separate publication.

PART III. NUCLEAR CONSIDERATIONS

1. The astronomical evidence on the abundance of DLiBeB

Before nuclear considerations concerning the synthesis of DLiBeB can be advanced it is necessary to summarize the astronomical evidence on their abundances. The great overabundance of Li in variable stars of the T Tauri class, stars nearing the end of their contracting phase, and located in dark nebulosity, is the most striking single astronomical datum to be explained. The Li^6/Li^7 ratio in the Sun appears to be near the terrestrial value (Greenstein & Richardson 1951). Both the line profile of the blended doublets of Li^6 and Li^7, and the wave length of the observed solar line, indicate that no large difference from the terrestrial Li^6/Li^7 ratio is possible. The isotope shift is 0·16 A and the separation of the line doublet the same. The observed wave length is 6707·83; the predicted mean wave length of the blend is:

$$\lambda = 6707{\cdot}00 + \frac{3}{2}\frac{1{\cdot}22 + 1{\cdot}46R}{1+R} \tag{10}$$

where $R = Li^6/Li^7$. The observed wave length for the blend gives $R = 0{\cdot}14$. The composite profile fits the observations poorly for $R = 0$; the wave length disagrees with the measured value for either $R = 0$ or ∞. A value $R = 1$ would approximately double the width of the observed line and be unacceptable on the basis of the profile. In consequence, $0{\cdot}05 < R < 0{\cdot}5$ is the plausible range. Very precise wave lengths, and photoelectric line profiles might permit a better determination of Li^6/Li^7. The isotope ratio and the low solar abundance of Li demonstrate that a nuclear process has burnt Li, but Li^6 even more rapidly than Li^7, in agreement with the large cross-section ratio for $Li^6(p,\alpha)$ relative to $Li^7(p,\alpha)$. (See Section III, 11.)

The elemental abundances of Li and Be have been measured by Greenstein and collaborators, and again recently by Goldberg, Müller & Aller (1960) (GMA). The f-value for Li I is reliable, and has been used by all investigators. GMA give log Li/Ca = −5·19; Greenstein and Richardson measured a larger equivalent width and used a different method of analysis. However, Greenstein & Tandberg-Hanssen (1954) (GTH) give log Li/Ca = −5·15 which might be revised downward to −5·30 by reduction of the equivalent width. Since the Ca/H ratios used in GMA and GTH are nearly identical, the probable value log Li/H = −11·00 to −11·15.

The Be abundance is difficult because of the location of all lines in the extreme ultraviolet. GMA used Be I, only, at λ3321; the f-values are the same as in GTH. Even the Be I lines are far outside the range for which GMA have reliable opacity and weight functions. They find log Be/Ca = −3·89. In the analysis of Be II, located by λ3130, GTH probably underestimated the depression of the ultraviolet continuum, and in addition used an f-value sum for the doublet 50 per cent too large (see Veselov 1949). Consequently, their abundance derived from Be II should probably be increased by a total factor of 3. Therefore, finally, the Be II lines give log Be/Ca = −3·84. Combining all determinations, log Be/H should lie in the range −9·65 to −9·75.

The only large-scale study of Li in normal stars, by Bonsack (1959), shows that in the K giants Li varies from star to star, probably because of convective mixing and the burning of any residual Li. However, the fact that in G8–K7 dwarfs Li is very weak or absent may either be caused by deep convection, or by a different early history and evolution for the fainter dwarfs than for the Sun (possibly lack of success in planet formation). At dK1, the lifetime of Li is computed to be about 10^9 years; it would be interesting to see whether Li exists in other G dwarfs than the Sun. The known T Tauri stars are on evolutionary tracks towards the A and F dwarfs and their super-abundance of Li is not found in any other type of stars.

On the other hand, among the A dwarfs, Bonsack (1961b) finds the Be abundance to be surprisingly variable. In α Lyr and α CMa the Be/Fe ratios are 0·11 and < 0·003 of the terrestrial value. On the other hand, the magnetic and spectrum variable, α^2CVn had Be/Fe = 2·4 times its terrestrial value. The low value in

α CMa may arise from its duplicity and the evolution of the white dwarf α CMaB; in α^2CVn it is probable that surface magnetic activity is connected with the Be excess.

In the T Tauri stars, D, He^3 and Be abundances cannot be studied, because of rotation and the faintness of these objects. But in all 12 stars studied (Bonsack & Greenstein 1960, Bonsack 1961a) the enhancement of Li is found, and is large. Since T Tauri stars are in late stages of their contraction with only 2 or 3 times their final main-sequence radius, element synthesis in the planetary regions, of the kind we discuss, should long have stopped, surface production and Li burning by convection may have started. In 5 of the brighter T Tauri stars, the abundance of Li is determined with respect to 7 lines of the elements Na, Ca, Fe, Ba, La. The range of Li excess, compared to the solar value, is 50 to 400 times (Bonsack & Greenstein 1960). The variation is possibly real, since the Ba abundance, based on one line also, seems to be determined within an error of a factor of two. The final log Li/H abundances in T Tauri stars lie in the range $-8{\cdot}4$ to $-9{\cdot}5$. Table I gives a brief resumé of the results in the Sun and normal and peculiar stars, for Li and Be.

Table 1

Logarithmic abundance ratios compared to hydrogen

Object	Li	Be
Sun	$-11{\cdot}00$ to $-11{\cdot}15$	$-9{\cdot}65$ to $-9{\cdot}75$
T Tauri Stars	$-8{\cdot}4$ to $-9{\cdot}5$	—
Magnetic A Star	—	$-9{\cdot}3$:
G–K dwarfs	< -12	
A dwarfs	—	$-10{\cdot}6$ to < -12

Another group of unstable stars are the red dwarfs with emission lines, the dMe stars. Some of these have giant flares and show relatively sharp H and He emission lines at normal phases. A conservative upper limit of D/H and He^3/He^4 less than 10 per cent has been found in a dMe star by Wilson (1961). Greenstein (1951) found that $He^3/He^4 < 0{\cdot}02$ in the Sun and the chromosphere. The D/H ratio in emission nebulae is less than 10^{-3}. Unfortunately, at present, no evidence exists concerning the abundance of B in the Sun or stars.

2. Difficulties in the synthesis of DLiBeB

In Part II, it was briefly noted that the relative abundances of the isotopes of LiBeB as well as the abundance of D relative to H indicate certain significant features concerning their synthesis which have hitherto escaped attention. The problem of finding *any* mechanism for the synthesis of these light nuclei is a very difficult one since DLiBeB are rapidly destroyed in hydrogen burning in stellar interiors even granting that they are produced at all. In the overall process $4H^1 \rightarrow He^4$ in main sequence stars, D is produced in equilibrium abundance given by $D/H \sim 10^{-17}$ a very small value compared to the terrestrial ratio $D/H = 1{\cdot}5 \times 10^{-4}$. In helium burning by $3He^4 \rightleftharpoons C^{12*} \rightarrow C^{12}$ in giant stars, the isotopes of LiBeB are by-passed. Thus the production of DLiBeB does not lie in the main line of element synthesis. The low abundance of these light nuclei attests to this.

It has been realized, as a consequence, that the synthesis must almost certainly occur through spallation by high energy, non-thermal particles interacting with relatively cool, moderate density material irrespective of the detailed astrophysical environment in which it takes place. (We use the term "spallation" throughout this paper to cover all mechanisms of production of DLiBeB and other nuclei at high energy. Thus the products of spallation include those ejected directly from nuclei, those which result from evaporation processes and those remaining as residues after the direct and evaporation processes.) The production of DLiBeB by spallation of heavier nuclei in the cosmic radiation is an example at hand. It can be imagined that the terrestrial and meteoritic DLiBeB were produced in a similar way. An upper limit for the temperature of the medium in which these nuclei are produced can be set by insisting that they be not destroyed by thermonuclear processes in whatever time scale is assumed for the synthesis. It has been suggested by Burbidge, Burbidge, Fowler & Hoyle (1957) (B^2FH) that DLiBeB are produced by spallation in supernova envelopes and the atmospheres of magnetic stars. The authors were frank enough to call this the *x*-process, where *x* is the unknown. They showed that the DLiBeB enrichment of the interstellar medium by this process fell short of the terrestrial abundances by at least a factor of 100. A recent treatment of the problem has been given by Bashkin & Peaslee (1961).

3. Synthesis of LiBeB

It is appropriate at this point to examine the abundances listed in Table 2. In this table, we have attempted to distinguish carefully between solar abundances

Table 2

Table of abundances (Si = 10^6)

	Solar Surface	Intermediate Stage	Terrestrial–Meteoritic
H^1	3.2×10^{10}	8×10^6	4×10^3
D^2	$< 10^6$	1 200	$0.6 (1.5 \times 10^{-4} H^1)$
He^3	$< 10^8$	< 15	—
He^4	3.2×10^9	800	—
Li^6	0.03	Terr–Met	7.4 (0.05)
Li^7	0.2	Terr–Met	92.6 (0.64)
Be^9	6	Terr–Met	20 (0.14)
B^{10}	—	Terr–Met	4.5 (0.03)
B^{11}	—	Terr–Met	19.5 (0.14)
C	1.7×10^7	$3 \times 10^3 (< 10^5)$	3×10^3
N	0.3×10^7	$10^3 (< 10^5)$	25
O	2.9×10^7	7.5×10^6	3.5×10^6
Si-group w/o Argon	2.5×10^6	Solar	Solar
Fe-group	1.6×10^5	Solar	Solar
Middleweight	10^3	Solar	Solar
Heavyweight (A > 100)	30	Solar	Solar

given in the second column and meteoritic–terrestrial abundances given in column four. Column three contains abundances derived in this paper for an intermediate stage in primitive terrestrial–meteoritic matter. The abundances beyond O are taken to be the same in the three cases. All abundances are given by number relative to Si = 10^6. The solar abundances are based on those quoted by Suess & Urey (1956) (SU), or observed by GMA. Certain relative isotopic abundances are taken from McKellar (1960). The meteoritic–terrestrial values are taken from SU or from Rankama & Sahama (1950). The H^1 abundance in column four is calculated from the amount of ocean water; the N abundance is several times the amount of atmospheric nitrogen, a rough allowance having been made for N in the Earth's crust and mantle. The relative isotopic abundances D^2/H, Li^6/Li^7, and B^{10}/B^{11} are terrestrial. For the LiBeB abundances we list in brackets the abundance relative to the total taken as unity.

Inspection of the LiBeB abundances leads to several interesting conclusions. It does not seem reasonable at all, on the basis of spallation production, that the even-A isotopes Li^6 and B^{10} should be so low in abundance relative to the odd-A isotopes Li^7, Be^9 and B^{11}. It is not unreasonable that $Be^9 \sim B^{11}$ but then why should $Li^7 \sim 5\ Be^9 \sim 5\ B^{11}$? An immediate explanation is given on qualitative grounds for these otherwise puzzling abundance ratios if it is assumed that nuclei were subjected to slow neutron reactions simultaneously with their production. Then the reactions $Li^6(n, \alpha)T^3(\beta^- \nu^*)He^3$ and $B^{10}(n, \alpha)Li^7$ which have large low energy cross sections will deplete Li^6 and B^{10} and enhance Li^7 and He^3. The thermal cross sections are given by Hughes & Schwartz (1958) as 945 barns and 3813 barns respectively. He^3 will be discussed later in Sections III, 11 and 15. The (n, α) reactions on Li^7, Be^9 and B^{11} are endothermic and do not occur at low energy. It will not be necessary to consider the reactions $He^3(n, p)T^3(\beta^- \nu^*)He^3$, $Be^7(n, p)Li^7$ or $N^{14}(n, p)C^{14}(\beta^- \nu^*)N^{14}$ which have thermal neutron cross sections of 5500 barns, 54000 barns, and 1·8 barns respectively. In the first case, and the last, the eventual beta decay replaces the original nucleus. In the second case, the reaction has a result equivalent to electron capture, $Be^7(e^-, \nu)Li^7$, and in general the electron capture occurs much faster than the neutron reaction. None of these reactions contribute seriously to the depletion of neutrons. This last statement is true for the $He^3(n, p)$ reaction only if helium escapes rapidly from the medium in which the neutron processes occur. The necessity for this is discussed in the appendix. In later sections, we will discuss $O^{17}(n, \alpha)C^{14}$, $Ne^{21}(n, \alpha)O^{18}$, and $Mg^{25}(n, \alpha)Ne^{21}$ as well as other neutron interactions among the heavier nuclei.

An alternative possibility involving proton reactions can be made to give the correct answer for the small Li^6/Li^7 ratio but fails in the case of the small B^{10}/B^{11} ratio. The $Li^6(p, \alpha)He^3$ reaction is about 100 times as fast as $Li^7(p, \alpha)He^4$ at $T = 1$ to 5×10^6 °C. Thus, it is conceivable that hydrogen burning might have differentially lowered Li^6 relative to Li^7. However, $B^{11}(p, \alpha)Be^{8*}(\alpha)He^4$ is about 4 times as fast as $B^{10}(p, \alpha)Be^7(e^-, \nu)Li^7(p, \alpha)He^4$. Thus, hydrogen burning would reduce B^{11} relative to B^{10} and such is not the case.

Thus, there would seem to be unmistakable qualitative evidence that the isotopes of LiBeB have been subject to neutron irradiation simultaneously with their synthesis by spallation. The question of simultaneity does involve quantitative comparisons with alternative possibilities which we have considered and rejected. This problem is treated in the appendix.

The evidence for the operation of neutron reactions leads straightforwardly to a reaction for the production of deuterons. This is the capture of neutrons in hydrogen, the reaction being $H^1(n, \gamma)D^2$. This reaction will be an important one in the detailed numerical analysis to follow.

As previously indicated, we have placed the nucleosynthesis of DLiBeB in the solar nebula at an early, active phase of the Sun's existence. However, it is to be emphasized that the detailed nuclear processes to be discussed seem to be indicated with considerable probability and will need to be invoked even if other astrophysical environments or circumstances are postulated. We attempt in the analysis which follows, to incorporate first of all only those nuclear considerations or "ground rules" which assume synthesis of the light nuclei by spallation simultaneously with neutron irradiation. Applications to the astrophysical model we have chosen will be made subsequently.

Let the total number of neutrons made available up to any given time during the synthesis be chosen as independent variable. It will, of course, appear in our analysis only in ratio to the number of nuclei irradiated by the neutrons. We designate this number by the symbol n. This number may well be a complicated function of position and time depending on the source of the neutrons, the conditions in the material in which DLiBeB are produced and so forth. This spatial and temporal variation is not our primary concern. In general, the neutrons may come from the same source as the high-energy particles and will interact with the quiescent material as do these particles. It is then required that the source be close enough to the quiescent material so that the neutrons do not decay in transit and that the neutrons have the same range as the high-energy particles. These requirements place severe restrictions upon the possible astrophysical circumstances for the synthesis. A more probable situation is that in which the neutrons are produced simultaneously and essentially in uniform ratio with the other spallation products by the high-energy particles. It will be shown in later sections that sufficient neutrons, indeed just the required number to explain the Li^6B^{10} abundance anomalies, are produced in this manner. In addition, it is the case that the thermalization and interaction of the neutrons occurs uniformly along the high-energy particle path in a distance small compared to the particle's range. Furthermore, this thermalization and interaction will occur before decay if the composition and density of the material in which the interactions occur is suitable. This will prove to be the case.

Consider now the nucleus Li^6 which is produced by spallation and is destroyed by the $Li^6(n, \alpha)$ reaction. Under the assumptions previously discussed, we can write

$$\frac{dLi^6}{dn} = \alpha_6 - \frac{f_r \sigma_6}{\sum_A \sigma_A N_A} Li^6. \qquad (11)$$

In this equation, the nuclear symbol, Li^6, is employed to indicate the number of Li^6 nuclei, taken as the dependent variable, as a function of the increasing number of neutrons produced throughout the synthesizing process. The quantity α_6 is the ratio of Li^6 nuclei to the number of neutrons produced in spallation. In includes not only those Li^6 nuclei produced directly in the ground state and particle stable excited states but also those which result from the short-lived decay ($\tau_{\frac{1}{2}} = 0{\cdot}85$ s) of the ground state of He^6. It does not include Be^6 production since Be^6 disintegrates into an alpha particle and two protons. The quantity α_6 represents a grand average over several variables. For each energy in the differential spectrum of incident particle energies, an average must be taken over the interval from this energy down to zero as the high-energy particle traverses its "range" in the quiescent material. An average must then be taken over the *differential* spectrum. If the energy loss cross section does not vary too rapidly with energy, these two averagings essentially represent an average over the *integral* spectrum. It will be shown later that the characteristic particle energy involved is in the intermediate range near 500 MeV per nucleon. In addition, an average for α_6 must be taken over all the possible interactions between the various types of incident particles and the various types of target particles in the quiescent material. Most important will be the interactions of high-energy protons and alpha-particles with abundant nuclei such as O^{16}, Mg^{24}, Si^{28}, Fe^{56}, etc. For our purposes, the important characteristic of α_6 is that it can be taken approximately as a constant independent of n. This requires only that no major modification in the relative number or energy of the interacting nuclei, incident or target, occur during the synthesis. We take this to be an essential feature of our point of view. There will, of course, be considerable modifications of the abundances of some nuclei, primarily those with large neutron capture cross sections, but since DLiBeB are so rare we will not require much destruction of the medium and heavy nuclei in order to produce them.

We turn now to consideration of the quantities appearing in the second term on the right-hand side of equation (11). The quantity f_r is the fraction of the neutrons produced which ultimately react with nuclei before they decay. In the applications described in this paper $f_r \approx 1$ and this matter is discussed in Section III, 10. The cross section for $Li^6(n, \alpha)T^3$ is indicated by σ_6. Other neutron interaction cross sections are designated by σ_A and the corresponding abundances by N_A. Mass numbers of the interacting nuclei are indicated by A. Only in special cases will it be necessary for us to distinguish isobars. With these definitions, the combination

$$\sigma_6 \mathrm{Li}^6 / \sum_A \sigma_A N_A$$

then represents that fraction of the interacting neutrons which interact with Li^6. Since thermal cross sections are always reported for the same neutron velocity (2200 m/s) *relative* to the interacting nucleus, the velocity terms in the numerator and denominator of this ratio cancel out. The coefficient of Li^6 is thus

$$f_r \sigma_6 / \sum_A \sigma_A N_A.$$

We take this to be a constant for essentially the same reasons advanced in regard to α_6. The major constituents contributing to the sum

$$\sum_A \sigma_A N_A$$

and to the evaluation of f_r will not be greatly changed during the synthesis mechanism. In our applications it will develop that $H^1(n, \gamma)D^2$ dominates in the determination of

$$\sum_A \sigma_A N_A.$$

Since D/H is small it will be clear that H is not changed appreciably during the synthesis. In this connection, it will be noted that only the ratios σ_A/σ_6 appear in the coefficient of Li^6. These ratios can be critically dependent upon resonance phenomena and thus on energy. On the other hand, in the presence of even a moderate excess of hydrogen the neutrons will be thermalized before capture. Thus, we will use thermal cross sections in our treatment. The relevant thermal energy will be given by the temperature of the quiescent medium. Reasons have been advanced in Part II which indicate that this temperature in the solar nebula was of the order of, or somewhat lower than, the standard temperature ~ 300 °K (0·025 eV) for which thermal cross sections are customarily quoted. The thermal cross sections tabulated by Hughes & Schwartz (1958) have been employed except where more recent data are available. It might be noted that the major neutron processes under consideration, $H^1(n, \gamma)D^2$, $Li^6(n, \alpha)T^3$, $B^{10}(n, \alpha)Li^6$, follow very roughly the usual $\sigma \sim 1/v$ law over an extended range of energies so that our assumption of thermalization at a particular temperature is actually not a critical one in this regard. Only cross section ratios come into the calculations.

With these considerations in mind, we will use the abbreviated symbol Σ to represent

$$\sum_A \sigma_A N_A$$

in what follows. We will also designate the number of neutrons which react by $n_r = f_r n$. Those which decay will equal $n(1-f_r)$. The integration of equation (11) is elementary under the stipulations of the previous paragraph and yields

$$\mathrm{Li}^6 = \mathrm{Li}_s{}^6\left(\frac{\Sigma}{\sigma_6 n_r}\right)\left[1 - \exp\left(-\frac{\sigma_6 n_r}{\Sigma}\right)\right] \tag{12}$$

$$\approx \mathrm{Li}_s{}^6\left(\frac{\Sigma}{\sigma_6 n_r}\right) = \alpha_6 n\left(\frac{\Sigma}{\sigma_6 n_r}\right) \text{ for } \sigma_6 n_r/\Sigma > 1. \tag{12'}$$

In these equations, $\mathrm{Li}_s{}^6 = \alpha_6 n$ is the total number of Li^6 nuclei produced in the synthesis. We now take n to be the total number of neutrons made available over the entire synthesis and which decay or interact. Similarly n_r is the total number of neutrons which interact with the nuclei whose total number is

$$\sum_A N_A.$$

Note that the effect of the neutron reaction is to reduce $\mathrm{Li}_s{}^6$ to Li^6 as the final number remaining at the end of the synthesis. We will find that the approximation (12′) holds for the cases which would seem to be of interest in which $\sigma_6 n_r/\Sigma$ turns out to be ≈ 4.

The differential equation and the solutions for B^{10} can now be written down with obvious notation in complete analogy to those for Li^6. We have

$$\frac{d\mathrm{B}^{10}}{dn} = \alpha_{10} - \frac{f_r \sigma_{10}}{\Sigma}\mathrm{B}^{10}. \tag{13}$$

There is one point which affects α_{10} which must be given some consideration, namely the long half-life of Be^{10}($\tau_{\frac{1}{2}} = 2{\cdot}7 \times 10^6$ yr). If the duration of the synthesis is several half-lives of Be^{10}, then α_{10} should include the production of this nucleus. For periods short compared to the half-life, α_{10} should not include the production of Be^{10} which will accumulate during the synthesis and then subsequently decay to B^{10}. The short-period case will be considered in the appendix. However, a period of synthesis less than $2{\cdot}7 \times 10^6$ years does not seem very probable. It has been pointed out in Part II that the Kelvin–Helmholtz contraction time to $R \sim 3 \times 10^{12}$ cm for the Sun is 5×10^6 years and that the effects of rotation of the condensing Sun and the magnetic fields in its surface layers probably increase this to $\sim 10^7$ years. It will be noted that α_{10} includes in any case the production of

$C^{10}(\tau_{\frac{1}{2}} = 10$ s). Thus B^{10} has three progenitors to two for Li^6. Integration of (13) yields

$$B^{10} = B_s^{10}\left(\frac{\Sigma}{\sigma_{10}n_r}\right)\left[1-\exp\left(-\frac{\sigma_{10}n_r}{\Sigma}\right)\right] \tag{14}$$

$$\approx B_s^{10}\left(\frac{\Sigma}{\sigma_{10}n_r}\right) = \alpha_{10}n\left(\frac{\Sigma}{\sigma_{10}n_r}\right) \quad \text{for} \quad \sigma_{10}n_r/\Sigma > 1. \tag{14'}$$

In these equations, $B_s^{10} = \alpha_{10}n$ is the total number of B^{10} nuclei produced in the synthesis. The approximation (14′) will be useful in cases of interest.

We are now in a position to extend our calculations to Li^7 which is produced in spallation as Li^7 and Be^7 and also results from $B^{10}(n, \alpha)Li^7$. Be^7 is transformed to Li^7 by $Be^7(e^-, \nu)Li$ with $\tau_{\frac{1}{2}} = 53$ days and also by $Be^7(n, p)Li^7$ which has a thermal cross section of 54000 barns. We will find in Section III, 4, that this yields a Be^7 lifetime for neutron interaction equal to 5×10^4 years. The cross section for $Be^7(n, \alpha)He^4$ is < 1 barn so this process can be neglected. He^7 is certainly particle unstable and even though produced momentarily and infrequently, it can be neglected. The differential equation is

$$\frac{dLi^7}{dn} = \alpha_7 + \frac{f_r\sigma_{10}}{\Sigma}B^{10} \tag{15}$$

$$= \alpha_7 + \alpha_{10}\left[1-\exp\left(-\frac{\sigma_{10}f_r n}{\Sigma}\right)\right]. \tag{16}$$

Integration to the end of the synthesis in which n neutrons are produced and in which n_r neutrons react yields:

$$Li^7 = Li_s^7 + B_s^{10} - \frac{\alpha_{10}\Sigma}{\sigma_{10}f_r}\left[1-\exp-\left(\frac{\sigma_{10}n_r}{\Sigma}\right)\right] \tag{17}$$

$$\approx \alpha_7 n + \alpha_{10}n - \alpha_{10}n\left(\frac{\Sigma}{\sigma_{10}n_r}\right) \text{ for } \sigma_{10}n_r/\Sigma > 1. \tag{17'}$$

We note from (14) and (17) that

$$Li^7 = Li_s^7 + B_s^{10} - B^{10}. \tag{18}$$

In these equations $Li_s^7 = \alpha_7 n$ and α_7 includes the spallation production of both Li^7 and Be^7.

For Be^9 and B^{11}, we can write

$$\frac{dBe^9}{dn} = \alpha_9 \tag{19}$$

$$Be^9 = Be_s^9 = \alpha_9 n \tag{19'}$$

$$\frac{dB^{11}}{dn} = \alpha_{11} \tag{20}$$

$$B^{11} = B_s^{11} = \alpha_{11}n. \tag{20'}$$

Be^9 is produced only as Be^9 since B^9 breaks up into $2\alpha + p$ and Li^9 beta decays ($\tau_{\frac{1}{2}} = 0{\cdot}17$ s) only to particle-unstable states of Be^9 which in turn break up into $2\alpha + n$. On the other hand, B^{11} results during synthesis from the short-lived beta decay of $C^{11}(\tau_{\frac{1}{2}} = 20$ min) and $Be^{11}(\tau_{\frac{1}{2}} = 13{\cdot}6$ s). Be^{11} has a rather low total binding energy so its production in spallation must be rare and hardly a contributing factor in the synthesis of B^{11}, which is to say that B^{11} essentially has only two progenitors as does Li^7. We remind the reader that the mass 8 nuclei, $Li^8Be^8B^8$, have transient existences beyond hope of analysis in the manner under discussion.

4. The number of neutrons and the neutron flux

It will be clear from the above discussion that in principle we could attempt to evaluate five quantities, $Li^6 \dots B^{11}$, in terms of eight other quantities, σ_6, σ_{10}, $\alpha_6 n$, $\alpha_7 n$, $\alpha_9 n$, $\alpha_{10} n$, $\alpha_{11} n$ and $n_r/\Sigma = nf_r/\Sigma$. The equations for Be^9 and B^{11} are clearly quite independent of the remaining equations which yield three relations, say (12′), (14′), and (18) between Li^6, Li^7, B^{10} and σ_6, σ_{10}, $\alpha_6 n$, $\alpha_7 n$, $\alpha_{10} n$ and n_r/Σ. Of these last quantities, only σ_6 and σ_{10} are definitely known from observations. Thus, rather than try to calculate the abundances on the basis of spallation observations for $\alpha_6 \dots \alpha_{10}$ and on estimates for n and n_r/Σ, we will reverse the procedure and use the observational evidence on the abundances, principally isotopic ratios, to yield some information concerning $\alpha_6 \dots \alpha_{10}$ and particularly about n_r/Σ. The quantity n_r/Σ is an important one because it quantitatively relates the neutron irradiation which modified the Li^6, Li^7, B^{10} abundances to the simultaneous modification in abundance for any nuclear species which is produced or destroyed by neutron interactions (see Section III, 13). In order to determine n_r/Σ, we will be ultimately forced to use some observational evidence on the α's. This will turn out to be the ratio α_7/α_6.

In order to come to grips with the problem, we turn to equation (18) and use approximations (12′) and (14′). After elementary algebraic manipulations, one can write

$$\frac{n_r}{\Sigma} = \frac{I_7 + I_{10}(B/Li)}{\sigma_6 I_6(\alpha_7/\alpha_6) + \sigma_{10} I_{10}(B/Li)} \tag{21}$$

$$= \frac{0{\cdot}926 + 0{\cdot}190(B/Li)}{70(\alpha_7/\alpha_6) + 725(B/Li)} \textit{ for terrestrial matter} \tag{21′}$$

where

$$I_6 = Li^6/Li = 0{\cdot}074, \text{ terrestrially}.$$

$$I_7 = Li^7/Li = 0{\cdot}926, \text{ terrestrially}.$$

$$I_{10} = B^{10}/B = 0{\cdot}190, \text{ terrestrially}.$$

$$\sigma_6 = 945\ b \text{ at } v_n = 2200 \text{ m/s}, kT = 0{\cdot}025 \text{ eV}, T = 293°K.$$

$$\sigma_{10} = 3813\ b \text{ under the same conditions}.$$

These last numerical values have been substituted into (21) to yield (21′). To obtain n_r/Σ from (21′) we still must make some assumption concerning α_7/α_6 and concerning the terrestrial ratio B/Li. There are no experiments or calculations available from which α_7/α_6 can be determined for the spallation of O^{16},Mg^{24}, $Si^{28} \dots Fe^{56}$ by intermediate energy protons. However, Dostrovsky, Fraenkel & Rabinowitz (1960) have given cross sections for the production of He^6, Li^6, Be^7 and Li^7 calculated by Monte Carlo methods for $Cu+p$ at 940 and 1840 MeV and for $Ag+p$ at 940 MeV.

Their results and experimental measurements for He^6 and Be^7 are given in Table 3. There are circumstances under which He^6 production in spallation is much less

Table 3

Experimental and calculated cross sections (mb) for the emission of He^6, Be^7, Li^6 *and* Li^7 *in proton spallation*

Target	Proton Energy MeV	$\sigma_s(He^6)$ Exp.	$\sigma_s(He^6)$ Calc.	$\sigma_s(Be^7)$ Exp.	$\sigma_s(Be^7)$ Calc.	$\sigma_s(Li^6)$ Calc.	$\sigma_s(Li^7)$ Calc.
Cu	940	2	2	4·4	5	14	10
Cu	1 840	4	6	11·7	11	26	18
Ag	940	4	6	2·5	7	24	16

Dostrovsky, Fraenkel & Rabinowitz, *Phys. Rev.*, **118,** 791 (1960).

than that of Be^7. However, it must be recalled that He^6 is a relatively "unstable" member of the mass 6 triad while Be^7 and Li^7 are the "mirror" mass 7 nuclei. It is reasonable that mass 6 should be produced as frequently as mass 7. It is well known that $Ne^{20}Ne^{21}Ne^{22}$ are produced about equally in spallation. We conclude that

$$\frac{\alpha_7}{\alpha_6} = \frac{\sigma_s(Be^7)+\sigma_s(Li^7)}{\sigma_s(He^6)+\sigma_s(Li^6)} \sim 1. \tag{22}$$

It is reasonable to expect a similar ratio at intermediate energies with other targets. Hence, we use $\alpha_7/\alpha_6 = 1$ in the calculations to follow but in Table 4 we show values of n_r/Σ for $\alpha_7/\alpha_6 = \frac{1}{2}$ and 2 in order to show the small effects of variations in this quantity.

Table 4

The determination of n_r/Σ

(Multiply entries by 10^{-3} *to obtain* n_r/Σ*)*

α_7/α_6	B/Li 0·1	B/Li 0·24	B/Li 0·5
0·5	8·7	4·6	2·5
1	6·6	4·0	2·3
2	4·5	3·1	2·0

The ratio B/Li = 0·24 has been given as an average value for silicate meteorites by Goldschmidt & Peters (1932). This ratio has been employed by SU (1956) in their tabulation of relative atomic abundances of the elements. For igneous rocks, Goldschmidt and Peters give B/Li = 0·03, while Lundegårdh (1946) gives 0·3, a factor of 10 higher. Chemical fractionation of B relative to Li has almost certainly occurred in the crust of the Earth. Thus, we know the terrestrial isotopic ratio for Li^6/Li^7 and B^{10}/B^{11} but there is considerable uncertainty in the terrestrial B/Li ratio. However, for reasons which will become apparent in the next section, we will take the meteoritic value B/Li = 0·24 as the "best" value in what follows. This assumes then that the "average" meteorite and the Earth formed from material which had the same high-energy charged particle and thermal neutron irradiation. It does not seem unreasonable, as a first approximation, to extend this statement to include all of the terrestrial planets. Thus throughout this paper the term *terrestrial matter* applies to the material of the meteorites, the Earth, and the other so called "terrestrial" planets. It is hoped that future investigations will lead to precise knowledge which will remove this blanket coverage. In Table 4, we show values of n_r/Σ for B/Li = 0·1 and 0·5 in order to show the small effects of variations in this quantity.

Table 4 shows that

$$n_r/\Sigma = 4{\cdot}0\times 10^{-3} \qquad \textit{for terrestrial matter} \tag{23}$$

for our "best" choices $\alpha_7/\alpha_6 = 1$ and B/Li = 0·24. Moreover, it shows that n_r/Σ does not change by much more than a factor of two for any combination of values in the range $\alpha_7/\alpha_6 = \frac{1}{2}$ to 2 and B/Li = 0·1 to 0·5.

The quantity n_r/Σ can be related to the neutron flux ϕ_n if it is recalled that the total number of neutrons reacting in the time t_s of the synthesis is given by

$$n_r = 10^{-24}\,.\,\phi_n t_s \sum_A \sigma_A N_A = 10^{-24}\,.\,\phi_n t_s \Sigma \tag{24}$$

again assuming that Σ remains approximately constant. The factor 10^{-24} changes the cross sections from barns to cm². Thus, the average neutron flux is given by

$$\phi_n = 10^{24}\,.\,n_r/t_s\Sigma \approx 10^7 \text{ neutrons/cm}^2\,\text{s} \qquad \textit{for terrestrial matter.} \tag{24'}$$

In the numerical evaluation, we have used $n_r/\Sigma = 4\times 10^{-3}$ and $t_s = 3\times 10^{14}$ s. The result indicates that terrestrial matter was irradiated by an effective slow neutron flux of $\sim 10^7 n/\text{cm}^2\,\text{s}$ over the interval of 10^7 years. The mean-life of a nucleus under these circumstances is $2{\cdot}5\times 10^9/\sigma$ years where σ is its thermal ($T = 293$°K) neutron cross section in barns.

5. Deuteronomy: the synthesis of deuterons

With the determination $n_r/\Sigma = 4\times 10^{-3}$, it is now possible to calculate α_7 to α_{11} and Li_s^6 to B_s^{11} using the abundances of Li^6 to B^{11} given by SU and taken by us to be appropriate for the material from which the Earth and the meteorites on the *average* formed. There is however an essential feature of the overall process under discussion which is revealed by the synthesis of deuterons simultaneously with that of the other light nuclei. This we will now discuss. The synthesis of deuterons occurs both by direct spallation and by neutron capture in ordinary hydrogen. The thermal cross section for this capture is $\sigma_1 = 0{\cdot}33\,b$. The cross section for $D^2 + n^1 \rightarrow T^3 + \gamma$ is only $\sim$ 0·6 mb so we neglect this reaction. Then we can write

$$\frac{dD^2}{dn} = \alpha_2 + \frac{f_r\sigma_1}{\Sigma} H^1, \tag{25}$$

where α_2 is the direct spallation production of D^2 relative to neutrons. Upon integration

$$\frac{D^2}{H^1} = \alpha_2 \frac{n}{H^1} + \frac{n_r\sigma_1}{\Sigma} = \frac{n_r\sigma_1}{\Sigma}\left(1 + \frac{\alpha_2}{f_r}\frac{\Sigma}{\sigma_1 H^1}\right)$$

$$\approx \frac{n_r\sigma_1}{\Sigma}\left(1 + \alpha_2 \frac{\Sigma}{\sigma_1 H^1}\right) \approx 1{\cdot}3\times 10^{-3}\left(1 + \alpha_2 \frac{\Sigma}{\sigma_1 H^1}\right). \tag{25'}$$

In the last approximation, we take $f_r \approx 1$ as discussed previously. (It will be noted that this approximation has not hitherto entered in our determination of n_r/Σ). The deuteron/neutron ratio in the spallation of intermediate and heavy nuclei has been discussed by Dostrovsky & others (1960) who give $\alpha_2 \sim 0{\cdot}1$. At the energies and hydrogen–helium concentrations of interest, there are negligible contributions from $p+p \rightarrow d+\pi^+$ and $p+\alpha \rightarrow d+He^3$. The ratio $\sigma_1 H^1/\Sigma$ represents the fraction of the interacting neutrons captured by hydrogen. In an excess of hydrogen, this ratio will approach unity and we will find later that it is approximately 2/3 when calculated for the amount of hydrogen which was present (as H_2O) when the irradiation of the primordial terrestrial material occurred. In any case, the direct spallation contribution is small and the final result is

$$D^2/H^1 = 1{\cdot}5\times 10^{-3} \quad \textit{in the terrestrial matter irradiated.} \tag{26}$$

It will be immediately noted this value is just an order of magnitude greater than the value given by SU.

$$D^2/H^1 = 1/6500 = 1{\cdot}5\times 10^{-4} \qquad \textit{terrestrially.} \tag{26$'$}$$

In addition, Boato (1954) has shown that D^2/H^1 in carbonaceous chondrites differs from the above value by no more than might be expected on the basis of differential fractionation processes in the formation of the Earth and the meteorites. It is essentially Boato's observations which led to the conclusion reached in Section III, 4, that the material of all the inner portions of the solar system received the same irridation. It is very gratifying that the neutron irradiation which was necessary to give the observed modification of the $Li^6Li^7B^{10}$ abundances was great enough to produce more than the observed D^2/H^1 ratio *in the material irradiated.* In fact, this must be an essential feature of any synthesis for DLiBeB because it will be clear that not all of the terrestrial material can have been irradiated by thermal neutrons totalling to such a number that $n_r/\Sigma = 4\times 10^{-3}$. Otherwise, nuclear species with cross sections greater than 1 000 barns would have been greatly reduced in number from their primordial number in the material of the solar nebula. At this point, one example will suffice, that of Gd^{157}, for which $\sigma(n,\gamma) = 2{\cdot}4\times 10^5$ barns. The cross section for Gd^{156} has not been measured but must be comparable to that for Gd^{158} which is 4 barns. On the other hand, the isotopic ratios relative to total Gd run Gd^{156}: Gd^{157}: Gd^{158} = 0·20: 0·16: 0·25. The odd A/even A ratio of somewhat less than unity seems to be quite normal. This and other examples (see Fowler & Hoyle 1960) indicate definitely that only a small fraction of the material was irradiated with thermal neutrons and then was subsequently mixed with the unaltered material. This can, of course, come about in several ways but most probably because the material had formed bodies large in radius compared to the range of the high-energy charged particles which produced the neutrons and because the neutrons were thermalized and captured close to their point of origin. Only the outer layers of these bodies or planetesimals was irradiated. The subject is treated semi-quantitatively in Section IV, 1. An estimate could be made for a dilution factor F_d, on the basis of examples like Gd^{157}. However, it would seem preferable to determine F_d on the basis of the terrestrial ratio for D^2/H^1. If we define F_d in general as ratio of the total amount of material to the amount irradiated, then we have

$$F_d = 10 \qquad \textit{for terrestrial matter} \tag{27}$$

and in general (25′) must be replaced by

$$\frac{D^2}{H^1} = \frac{\sigma_1}{F_d}\frac{n_r}{\Sigma}\left(1+\alpha_2\frac{\Sigma}{\sigma_1 H^1}\right) \approx \frac{\sigma_1}{F_d}\frac{n_r}{\Sigma}. \tag{25''}$$

It will be clear from the analysis in Section III, 4 and particularly from the discussion in the appendix of this paper that the evaluation of n_r/Σ depends to some extent on the values used for the relative spallation yields of LiBeB or alternatively on what the relative abundances of LiBeB are taken to be in terrestrial matter. Additional experimental measurements on spallation yields and/or observations on abundances are required before n_r/Σ can be determined with greater accuracy. However, it will be noted that (25″) indicates that the quantity $n_r/F_d\Sigma$ is given for *terrestrial* matter to fairly high precision if it is accepted that terrestrial D^2 was produced in the manner described in this paper and in particular was produced primarily through $H^1(n, \gamma)D^2$ rather than as a direct spallation product. The determinations given above yield

$$\frac{n_r}{F_d\Sigma} = 4\times 10^{-4} \qquad \textit{for terrrestrial matter.} \tag{28}$$

This result indicates that n_r/Σ divided by F_d is fixed by the D^2/H^1 ratio and that any future change in n_r/Σ will require a corresponding change in F_d. In Section III, 13 it will be shown that only $n_r/F_d\Sigma$ need be known to calculate neutron irradiation effects as long as the thermal neutron cross section involved is not too large.

As noted previously, it is the observation of Boato (1954) that D^2/H^1 in carbonaceous chondrites is approximately equal to the terrestrial value which led us to assume the same irradiation parameters for meteoritic and terrestrial matter in the planetesimal stage. It is seen now that D^2/H^1 essentially determines only $n_r/F_d\Sigma$ and not n_r/Σ and F_d independently. It is difficult to estimate the chance that differences in n_r/Σ and F_d might just compensate. Actually, variations in these quantities by less than a factor of 2 are all that can reasonably be expected for the inner parts of the solar system. Boato did observe variations in the D^2/H^1 ratio ranging from −13 per cent for the Cold Bokkeveld meteorite to +36 per cent for the Ivuna meteorite. These variations are most probably due to fractionation effects but there may also be differences surviving from the planetesimal irradiations. In any case, it is assumed throughout this paper that n_r/Σ and F_d were the same for meteoritic and terrestrial material including all of the inner planets. A solution to the problem will be reached only through extensive studies of Li^6/Li^7, B^{10}/B^{11}, and Li/Be/B in meteorites and in correlations of these ratios with the D^2/H^1 ratios preferably remeasured on common samples. *The role of planetary space research will also be apparent.*

All of the calculations to this point have been based on the assumption that the material from which the solar system formed did not contain DLiBeB. The results suggest that the interstellar medium did not and presently does not contain DLiBeB. It is difficult to reverse the line of reasoning and to ask what amount of DLiBeB could have existed in the primordial solar material without obscuring the effects of the production in the planetesimals. For example, interstellar D^2/H^1 could equal one-half that on the Earth both now and when the solar system formed and it should only be necessary to double F_d increasing it from 10 to 20. This dilution factor cannot be increased much above 20 without necessitating unreasonable amounts of irradiation of the planetesimals. A somewhat more stringent limitation can be placed on the amount of LiBeB in the interstellar medium. Both the T Tauri observations and our calculations rule out more than 10 per cent of the terrestrial–meteoritic LiBeB abundance divided by the solar H abundance so that LiBeB/H $\lesssim 5 \times 10^{-10}$ in the interstellar medium.

No evidence has been presented in this paper which indicates that the material of the inner planets or parent bodies of the meteorites received an irradiation different than the material of the Earth in the planetesimal stage. However, there are good reasons to believe that the material of the outer planets contained much more hydrogen than that of the inner planets during irradiation. As a consequence, the DLiBeB production during irradiation was small and the outer planets should show only "primordial" DLiBeB. This is to say that the limits which apply to the DLiBeB abundances in the interstellar medium also apply to these abundances in the outer planets. Implicit in this argument is the assumption that galactic nucleosynthesis has not greatly enriched the interstellar medium in the last 5×10^9 years.

It is perhaps well to clarify a matter of terminology at this point. We use the adjectives *primordial*, *primitive*, and *primeval* in connection with solar system abundances to indicate the abundance distribution in the material from which the solar system originally formed. The heavy elements in this material were synthesized from hydrogen in the galaxy in the processes described by B²FH. Nucleosynthesis during the early history of the solar system changed the primitive abundances in the manner under discussion in this paper.

6. Calculation of the spallation abundances and comparison with the cosmic radiation

Equations (12), (14), (17), (19′), and (20′) must be similarly modified to include $1/F_d$ if the abundances on the left-hand side are to refer to abundances after both irradiation and subsequent dilution. With these modifications, Li_s^6 to B_s^{11} can finally be calculated relative to Si $= 10^6$ in the material irradiated. The values so determined are given in Table 5A. In this table, $L_s = 1\,650$ represents the sum of the five isotopes of the three light elements produced in spallation. In

Table 5A

Spallation yield relative to Si $= 10^6$

Li_s^6	Li_s^7	Be_s^9	B_s^{10}	B_s^{11}	L_s
283	283	200	689	195	1 650

Li_s/L_s	Be_s/L_s	B_s/L_s
0·34	0·12	0·54

Table 5B are shown the relative abundances of the light elements calculated for various values of n_r/Σ. It will be most interesting to ascertain whether isotopic abundances corresponding to any of these values are found in parts of the solar system in the future. It should be recalled at this point that n_r is a measure of *all* spallation processes as long as complete thermalization occurs, while $\Sigma = \Sigma\, \sigma_A N_A$ depends on the *relative* composition of the material irradiated. Thus n_r/Σ is changed by a change in the total irradiation of material of given composition. In addition, even if the irradiation be the same, n_r/Σ is different for target materials having different H/Si ratios, for example.

A check on the relative spallation production of LiBeB cannot be obtained from current high-energy accelerator data. However, a comparison can be made with the charge spectrum of the heavy particles in the cosmic radiation at the top of the Earth's atmosphere. The relativistic LiBeB in this spectrum (no isotopic separation is possible) are thought to result primarily from the collision of relativistic CNO

Table 5B

Relative abundances of the light nuclei vs. available neutrons

n_r/Σ	D^2/H^1	Li^6/L	Li^7/L	Be^9/L	B^{10}/L	B^{11}/L	Li^6/Li^7	B^{10}/B^{11}
0	0	·17	·17	·12	·42	·12	1·0	3·5
$0·5\times10^{-3}$	$0·2\times10^{-4}$	·14	·42	·13	·19	·12	0·34	1·6
1	0·4	·12	·51	·13	·11	·13	0·23	0·89
2	0·8	·09	·59	·13	·06	·13	0·14	0·46
4	1·5	·05	·64	·14	·03	·14	0·08	0·23
8×10^{-3}	3×10^{-4}	·03	·67	·14	·02	·14	0·04	0·11
Large	Large	0	·71	·15	0	·14	0	0

nuclei from the cosmic ray source with "stationary" atoms, primarily H and He, in interstellar space. In the interactions of high-energy particles from the Sun with the solar nebula we have similar events occurring not only between relativistic CNO nuclei and "stationary" H and He, but also between relativistic H and He nuclei and "stationary" medium weight nuclei. Under an appropriate change of coordinates, the results in the two cases are identical for an exact one to one correspondence between abundances in the Sun and in the solar nebula and for a similar velocity spectrum for each particle (same energy/nucleon). This last condition seems to be the case in the cosmic radiation. There are, of course, differences in composition in that the Sun is primarily H, He, C, N, O, Ne, Mg, Si, Fe, etc., while the planetesimals in the solar nebula were primarily H, O, Mg, Si, Fe, etc. These differences are hardly important for high-energy interactions. In Table 6, we tabulate the results of some recent photographic emulsion measurements on the ratios Li_{cr}/L_{cr}, Be_{cr}/L_{cr} and B_{cr}/L_{cr} in the primary cosmic radiation. The bracketed numbers are the actual number of tracks observed in the emulsions

Table 6

Primary cosmic ray LiBeB ratios

	Li/L	Be/L	B/L
Freier & others (1959)	·22 (10)	·18 (8)	·60 (27)
Engler & others (1958)	·32 (22)	·22 (15)	·46 (32)
Appa Rao & others (1958)	·22 (34)	·13 (19)	·65 (100)
Tamai (1960)	·25 (25)	·35 (35)	·40 (40)
Koshiba & others (1958)	·24 (19)	·34 (27)	·42 (34)
Fowler & others (1957)	·23 (15)	·29 (19)	·48 (32)
Dainton & others (1952)	·19 (50)	·33 (88)	·48 (130)
Average	·24	·26	·50
Corrected Average ($1·67\times Li$)	·35	·22	·43
Spallation Yields (Table 5A)	·34	·12	·54

(Number of events in brackets)

and the unbracketed numbers are the fraction of the total. In taking the average, we have weighted the results of each group of observers equally. Most of the observers suggest that there is a bias in their measurements against the detection of Li tracks which are not as heavy as the Be and B tracks. Koshiba & others (1960) note a relative efficiency of only 60 per cent for Li tracks. The "corrected" average is given in the last line of the table. The agreement with the spallation fractions calculated previously is satisfactory. The relatively large number of Be nuclei "observed" in the cosmic radiation may be due to poor resolution in the charge spectrum. Poor resolution tends to raise "valleys" and lower "peaks". Both the cosmic ray fractions and the spallation fractions are quite different than the fractions observed terrestrially, namely Li: Be: B = 0·69: 0·14: 0·17. The effects of the thermal neutrons are clearly apparent.

7. Spallation cross sections

The spallation cross sections for the production of the various isotopes of LiBeB are proportional to the yields given in Table 5A. It is appropriate at this point to combine the information thus obtained on cross sections with the experimental information which is available concerning spallation cross sections at intermediate energies not only for LiBeB but also for other elements. This is done in Table 7.

Before discussing the data of Table 7, there is one point concerning the relative spallation yields in Table 5A which requires some comment. It will be noted that B^{10} is produced approximately three times as frequently as the other nuclei. This is probably in part due to the fact that B^{10} has three progenitors, $B^{10}C^{10}Be^{10}$, in the spallation while the other nuclei have at most two. In addition, B^{10} has several low lying bound states and in particular, its ground state has a spin $J = 3$ which gives it a relatively high *a priori* statistical weight factor, $2J+1 = 7$ (see Drostovsky & others (1959)). It does not seem unreasonable that B^{10} nuclei should have a relatively high yield in spallation. Experimental evidence on this point would be most welcome. If it develops that $B_s^{10} \sim B_s^{11}$ then it will be necessary to accept an irradiation time $< 2{\cdot}7 \times 10^6$ years so that Be^{10} will preserve some B^{10} in the manner discussed in the appendix. The appendix contains discussion of the case $Li_s^6 \sim Li_s^7 \sim Be_s^9 \sim B_s^{10} \sim B_s^{11}$ for which $n_r/\Sigma = 6{\cdot}6 \times 10^{-3}$.

Table 7 has been prepared by making a detailed survey of the literature references given in the review article by Miller & Hudis (1959). Intermediate energy proton data from 100 to 500 MeV were used wherever possible. The total interaction cross sections on which Table 7 is based are somewhat larger than usually given for cosmic ray protons. The solar protons are less energetic than cosmic ray protons and, in general, diffraction and reduced transparency make their cross sections somewhat larger. However, fragmentation probabilities for the heavier fragments are somewhat smaller because of the lower energy available and this tends to compensate in this case. Column 2 lists the radioactive nuclei for which cross sections are measurable at the mass numbers given in column 1. Stable nuclei of these mass numbers are given in column 5. The effective spallation cross sections listed in column 6 are typical of any reasonable distribution of incident particles and target nuclei. For reasons to be discussed in Section III, 8, the target nuclei are taken to 75 per cent O^{16} by number and 25 per cent Si-group by number. The appropriate experimental or estimated cross sections are given in columns 3 and 4 respectively. In general, the effective cross sections for the eventual production of the stable nucleus at a given mass number is found by assuming that the direct

Table 7

Intermediate energy spallation cross sections (mb) and abundances (Si = 10^6)

1	2	3	4	5	6	7	8	9	10
Mass	Activity	Proton Cross Section (mb) O^{16}	Si-group	Stable Nucleus	Effective Spallation Cross Section (mb)	Spallation Yield N_s	Neutron Reactions	Overall Yield N_r	Planetesimal Condensation N_p
1	n^1	800	1 200	H^1	900			(1 650 n)	8×10^6
2	—	(100)	(100)	D^2	100	180	$H^1(n, \gamma)$	1 200	0
3	T^3	38	23	He^3‡	70	130	$Li^6(n, \alpha)$	150(esc)	0
4	—	(400)	(400)	He^4	400	740	$Li^6B^{10}(n, \alpha)$	820(esc)	0
6	He^6†	5	1	Li^6	(15)	28	$Li^6(n, \alpha)$	7·4	0
7	Be^7	10	2	Li^7	15	28	$B^{10}(n, \alpha)$	92·6	0
9	—			Be^9	(11)	20		20	0
10	C^{10},Be^{10}	(10)	3	B^{10}	(38)	69	$B^{10}(n, \alpha)$	4·5	0
11	C^{11}	7	3	B^{11}	11	20		19·5	0
Σ(6–11)					90	165		144	0
13	N^{13}†	6	(5)	C^{13}	18	33		33	0 (?)
15	O^{15}	31	(7)	N^{15}	50	90		90(esc)	0 (?)
17	F^{17}		(8)	O^{17}	4	7	$O^{17}(n, \alpha)$	7	1 600
18	$F^{18}(Ne^{18})$		10	O^{18}	5	9	$Ne^{21}(n, \alpha)$	9–12	8 000
19	$Ne^{19}(O^{19})$		(10)	F^{19}	5	9		9	1 600
20	(F^{20}, Na^{20})		(40)*	Ne^{20}	10	18		18(esc)	10^{-4}(atmos)
21	Na^{21}		(10)	Ne^{21}	5	9	$Ne^{21}(n, \alpha)$	6–9(esc)	3×10^{-7}(atmos)
22	$Na^{22}(Mg^{22})$		12	Ne^{22}	6	11	$Mg^{25}(n, \alpha)$	20(esc)	10^{-5}(atmos)
23	(Ne^{23},Mg^{23})		(12)	Na^{23}	3	5		5	4×10^4
24	Na^{24}		15	Mg^{24}	8	15		15	7×10^5
26	Al^{26}		(60)	Mg^{26}	15	28		28	1×10^5
36	Cl^{36}		5	A^{36}	2	4	$Cl^{35}(n, \gamma)$	90(esc)	2×10^{-4}(atmos)
38	(Cl^{38}, K^{38})		—	A^{38}	3	6		6(esc)	4×10^{-5}(atmos)

( ) Contribution of bracketed activities neglected (column 2).
( ) Estimated cross sections (columns 3 and 4).
( ) Cross sections necessary to give observed abundances (column 6).
* $Mg^{24}(p, p\alpha)Ne^{20}$ assigned a cross section of 100 mb.
† Anomalously low spallation yields; only one stable state.
C^{13} direct yield = $2N^{13}$ yield.

‡ He^3 direct yield = $3/4T^3$ yield; 10 mb is added to include the $He^4(p, d)He^3$ reaction.
esc: Escapes from the planetesimals.
atmos: Atmospheric abundances are taken to be lower limit in planetesimals.
Except where noted, stable product yield = activity yield.
Note two activities at mass 10.

cross section for the stable product is the same as that for the radioactive product. The two cross sections are then added to give the effective value. Exceptions are noted. In the case of the LiBeB isotopes, the measured cross sections for Be^7 and C^{11} yield effective cross sections for the production of Li^7 and B^{11}. The other cross sections in brackets are those required to give the relative yields given in Table 5. The total cross sections for LiBeB production is seen to be 90 mb while the spallation yield after dilution by a factor of 10 is 165 on the Si = 10^6 scale. The ratio 165/90 thus makes it possible to correct effective cross sections to the spallation yields *after dilution* given as N_s in column 7. Neutron reactions are listed in column 8 and the final overall irradiation yields are given as N_r in column 9. These are to be compared with the abundances which condensed originally in the planetesimals and which are listed as N_p in column 10. At this point, attention is called to the effective cross sections for neutrons, deutrons, and light nuclei which are 900, 100 and 90 mb respectively. These results afford substantiation of the ratio $\alpha_2 = D^2/n \sim 0{\cdot}1$ and $\alpha_L = L_s/n \sim 0{\cdot}1$, which have been used in the analysis in previous and following sections of this paper.

8. The amount of hydrogen present during the synthesis of terrestrial DLiBeB

That some hydrogen was present during the synthesis of terrestrial DLiBeB is qualitatively clear for several reasons. The hydrogen is effective in thermalizing the neutrons before decay (see Section III, 10). Some hydrogen is necessary to yield deuterons upon neutron capture except in the unlikely event that $F_d = 1$ when direct spallation will suffice. However, it will also be qualitatively clear that the amount of hydrogen could not have been equal to the overwhelming amount in primordial solar matter since then all neutrons would have been absorbed in hydrogen and none would have been available for $Li^6(n, \alpha)T^3$ or $B^{10}(n, \alpha)Li^7$. For example, six times as much H^1 would have reduced n_r/Σ by a factor of four; see Table 5, B for the result of this reduction by comparing the rows for $n_r/\Sigma = 4 \times 10^{-3}$ and 1×10^{-3}.

A quantitative treatment of this problem is possible using the equations already derived. Once again let L_s represent all of the light nuclei produced in spallation and let $\alpha_L = \alpha_6 + \alpha_7 + \alpha_9 + \alpha_{10} + \alpha_{11}$. Then

$$L_s = \alpha_L n \approx \alpha_L n_r \quad \text{for} \quad f_r \approx 1. \tag{29}$$

For future reference, we note that

$$L \approx \frac{1}{F_d}[L_s - Li_s^6(1 - \Sigma/n_r\sigma_6)] \quad \text{for} \quad \sigma_6 n_r/\Sigma > 1 \tag{30}$$

where the second term in the square brackets represents the Li^6 produced in spallation but transformed to He^3 by $Li^6(n, \alpha)T^3\ (\beta^- \nu^*)He^3$. Divide (29) by the abundance standard Si to establish:

$$\frac{L_s}{\mathrm{Si}} = \frac{\alpha_L n_r}{\mathrm{Si}} = \alpha_L \frac{n_r}{\Sigma}\frac{\Sigma}{\mathrm{Si}} = 4{\cdot}0 \times 10^{-3}\alpha_L \frac{\Sigma}{\mathrm{Si}} = 1{\cdot}65 \times 10^{-3} \tag{31}$$

or

$$\frac{\Sigma}{\mathrm{Si}} = \frac{0{\cdot}41}{\alpha_L}. \tag{32}$$

In the numerical evaluation we have read L_8 from the last column of Table 5, A. To proceed further it is necessary to evaluate the contribution of all nuclei to

$$\Sigma = \sum_A \sigma_A N_A.$$

This will now be attempted.

Table 8 lists the neutron interaction cross sections at thermal energies (~ 0.025 eV or $\sim 300°$) for light nuclei. To the approximation that all cross sections vary inversely as the velocity we can use these cross sections at lower temperature since only cross section ratios enter into our calculations. On the left-hand side

Table 8

Thermal neutron interaction cross sections for light nuclei

Nucleus	Reaction	Product	σ	Nucleus	Reaction	Product	σ
H^1	n, γ	D^2	0·332 b	C^{12}	n, γ	C^{13}	3·3 mb
D^2	n, γ	T^3	0·57 mb	C^{13}	n, γ	C^{14}	0·7 mb
T^3	—	—	0	N^{14}	n, p	C^{14}	1·8 b
					n, γ	N^{15}	0·08 b
He^3	n, p	T^3	5400 b	N^{15}	n, γ	N^{16}	24 μb
He^4	—	—	0	O^{16}	n, γ	O^{17}	<0·2 mb
Li^6	n, α	T^3	945 b	O^{17}	n, α	C^{14}	0·4 b
Li^7	n, γ	Li^8	33 mb	O^{18}	n, γ	O^{19}	0·2 mb
Be^7	n, p	Li^7	54000 b	F^{19}	n, γ	F^{20}	9 mb
Be^9	n, γ	Be^{10}	10 mb	Ne^{20}	n, γ	Ne^{21}	<7 mb
B^{10}	n, α	Li^7	3813 b	Ne^{21}	n, α	O^{18}	<300 b
B^{11}	n, γ	B^{12}	< 50 mb	Ne^{22}	n, γ	Ne^{23}	36 mb

of Table 8 $D^2Li^6Li^7Be^9B^{10}B^{11}$ can be neglected in calculating Σ because they never build up to significant abundances. Small corrections for Li^6 and B^{10} can be made later. T^3 and He^4 do not capture neutrons. The case of He^3 is discussed in the appendix; we will here assume that it escapes from the primitive planetesimals before interacting with neutrons. In spite of its large cross section Be^7 decays before interacting with neutrons. On the right-hand side of Table 8, only N^{14} and perhaps Ne^{21} have significant cross sections. Note that the cross section for O^{16} is very low in keeping with its double closed shell structure. Ne^{21} is very rare. The amount of N^{14} in the material under consideration depends upon the detailed model assumed during the irradiation process. In principle, it could range from the solar value to the terrestrial value given in Table 2. We will retain the N^{14} abundance as an unknown for the time being. The total interaction cross section for N^{14} is $\sigma_{14} = 1{\cdot}88$ barns.

Table 9 lists the neutron interaction cross sections (barns) and abundances for the Si-group and Fe-group elements. We take the relative abundances for these elements to be the same for solar and terrestrial material and thus for any intermediate stages. We do anticipate somewhat in neglecting the argon abundance. Argon did not condense in the intermediate stage. For the Si-group, we use the abundances of SU, and for the Fe-group we use those of GMA. This is because the latter abundances can be understood quantitatively in terms of the equilibrium process of B^2FH. (It should be noted that discrepancies between meteoritic and solar abundances are still serious.) In the last line of Table 9, we note that our effective cross section σ_{eff} defined by $\sigma_{eff}Si = \Sigma\sigma_A N_A$ for $A > 22$ has the value 1·35 barns. Thus

$$\Sigma = \sum_A \sigma_A N_A \approx \sigma_1 H^1 + \sigma_{14} N^{14} + \sigma_{eff} Si \tag{33}$$

where $\sigma_1 = 0{\cdot}332$ barns, $\sigma_{14} = 1{\cdot}88$ barns $= 5{\cdot}7\ \sigma_1$, $\sigma_{eff} = 1{\cdot}35$ barns $= 4{\cdot}1\ \sigma_1$.

Table 9

Thermal neutron interaction cross sections (barns) and abundances for Si-group and Fe-group elements

Si-group (SU)				Fe-group (GMA)			
Element	σ_A	$N_A/10^6$	$\sigma_A N_A/10^6$	Element	σ_A	$N_A/10^6$	$\sigma_A N_A/10^6$
Na	·52	·044	·023	Sc	24·0	$2{\cdot}1 \times 10^{-5}$	·001
Mg	·063	·912	·057	Ti	5·8	$1{\cdot}5 \times 10^{-3}$	·009
Al	·23	·095	·022	V	5·0	$1{\cdot}6 \times 10^{-4}$	·001
Si	·16	1·000	·160	Cr	3·1	$7{\cdot}2 \times 10^{-3}$	·022
P	·20	·010	·002	Mn	13·2	$2{\cdot}5 \times 10^{-3}$	·033
S	·52	·375	·195	Fe	2·53	0·12	·304
Cl	33·6	·0088	·298	Co	37·0	$1{\cdot}4 \times 10^{-3}$	·052
A	·66	—	—	Ni	4·8	$2{\cdot}6 \times 10^{-2}$	·125
K	2·07	·003	·006	Cu	3·8	$3{\cdot}5 \times 10^{-3}$	·013
Ca	·44	·049	·021	Zn	1·1	$8{\cdot}0 \times 10^{-4}$	·001
Si-group	⟨·31⟩	2·50	·784	Fe-group	⟨3·45⟩	0·163	·561
Both groups	⟨·51⟩	2·66	1·35				

Equations (32) and (33) can now be combined to yield

$$\frac{H^1}{Si} = \frac{1{\cdot}24}{\alpha_L} - 5{\cdot}7\frac{N^{14}}{Si} - 4{\cdot}1. \tag{34}$$

From this equation it will be clear that the ratio H^1/Si depends critically on α_L and on the amount of N^{14}. We have retained the term in N^{14} in order to indicate its importance. If $\alpha_L = 0{\cdot}1$ then N^{14}/Si cannot exceed 1·5. This rules out the solar value $N^{14}/Si = 3$. However there are good reasons to believe that little N condensed in the planetesimals. See Section III, 12 for elaboration of this point. Thus we neglect N^{14} and (34) becomes

$$\frac{H^1}{Si} = \frac{1{\cdot}24}{\alpha_L} - 4{\cdot}1. \tag{34'}$$

The data of Table 7 indicate $\alpha_L = 0{\cdot}1$ so $H^1/Si = 8{\cdot}3$ or $H^1 = 8{\cdot}3 \times 10^6$. This yields $\Sigma = 4{\cdot}1 \times 10^6$ barns abundance units and $n = 1{\cdot}65 \times 10^4$ neutrons per abundance unit (10^6 Si nuclei). At this point we note that once B^{10} had built up to its equilibrium abundance $= 45$ before dilution, it contributed $45 \times 3\,813 = 0{\cdot}17 \times 10^6$ to Σ and similarly Li^6 contributed $74 \times 945 = 0{\cdot}07 \times 10^6$. Correcting for these contributions reduces H^1 somewhat and so we round off to $H^1 = 8 \times 10^6$.

There is, of course, some uncertainty in the value we have chosen for α_L, the ratio of light nuclei to neutrons produced in spallation. In fact this quantity could be reduced by a factor of 2 or increased by a factor of 2 without doing violence to the available experimental data. The possible range is thus $0{\cdot}05 < \alpha_L < 0{\cdot}2$.

Eq. (34′) then yields $2 < H^1/Si < 20$ or $2\times 10^6 < H^1 < 2\times 10^7$ with $H^1 = 8\times 10^6$ our best estimate.

We have thus been able to establish within a factor of 10 the abundance of H during the irradiation of the material which was eventually to form the Earth. It will be noted that this range for H falls *between* the values $3{\cdot}2\times 10^{10}$ in solar material and 4×10^3 in terrestrial material as listed in Table 2. *The* DLiBeB *abundances demand a stage for primitive terrestrial material intermediate between the original solar and the present terrestrial composition.* Suess (1949), Brown (1952) and Urey (1952, 1957) have reached this same conclusion from chemical and geophysical considerations. The reader is referred to Professor Urey's comments at the end of this section. The implications of this conclusion will be discussed briefly in the final parts of this paper. At this point, it is sufficient to emphasize that the reduction in the H abundance from that in the primitive solar material can be brought about, as far as we can see, only by condensation of solids from the primitive gas. We place the separation of the solids from the gases in an intermediate stage *before the formation of the Earth.*

It is noteworthy that $H = 8\times 10^6$, is the order of magnitude, in fact close to twice the value, of the present terrestrial value for oxygen, $O = 3{\cdot}5\times 10^6$, given in Table 2. This would be expected if the metals were not oxidized and if the hydrogen and oxygen were trapped in the well-known chemical combination, H_2O, presumably as ice, in the primitive planetesimals of pre-terrestrial material. (We presume that the same hydrogen to oxygen ratio held throughout the shielded inner parts of the planetesimals as through the irradiated outer parts.) On this point of view, in the subsequent formation of the Earth, most of the hydrogen, but very little or none of the oxygen was lost, the oxygen serving to oxidize silicon and the metals.

However it would seem highly unlikely that Mg and Si were not oxidized before or shortly after incorporation in the planetesimals. Considerable chemistry certainly occurred in the irradiated planetesimals over 10^7 years. We retain the idea that the hydrogen was trapped as H_2O in the amount $\sim 4\times 10^6$ molecules. This introduces excess oxygen as well as hydrogen which must be removed before, during, or shortly after the formation of the Earth.

If the loss took place from the planetesimals before aggregation to form the Earth then three distinct processes occurred in temporal sequence: first, the irradiation which has been under discussion; second, complete mixing of the water in the surface layer and internal material by diffusion; third, transport of the water to the surface and evaporation therefrom. It is not at all impossible that such a sequence occurred. The planetesimals were irradiated for a period of 10^7 years at very low temperature ($\sim$ 150°K) while the Sun was subluminous. This was followed by a somewhat longer interval in which the luminosity of the Sun rose to a maximum and then dropped slightly to its early main sequence value. In this interval diffusion and then loss could have occurred. If all of this occurred, then it must be realized that the Earth formed from "baked out" planetesimals.

An alternative is the loss of water during the formation of the Earth. The problem is one of considerable uncertainty but at least the possibility exists that H_2O molecules acquired escape velocities during most of the accumulation of the Earth. High temperatures resulted from the release of gravitational energy as the planet formed. During the terminal stages, at somewhat lower temperatures, H_2O could probably not escape but would be decomposed by sunlight at high altitude, the hydrogen escaping and leaving an atmosphere containing oxygen. Oceanic water was clearly retained once the temperature had dropped enough.

Our calculations would seem to rule out that all of the H_2O in the primitive terrestrial gas condensed in the planetesimals since this would require $H_2O \sim 3 \times 10^7$ and $H \sim 6 \times 10^7$. This would demand $\alpha_L \sim 0{\cdot}02$ or one light nucleus per 50 neutrons, an unreasonably low value. Furthermore, the calculated hydrogen cannot match the hydrogen in the H_2O, NH_3, and CH_4 indicated by the solar CNO-abundance. This would require $H > 10^8$ which seems well outside the realm of possibilities. Conditions must have been such that very little NH_3 or CH_4 and only about 15 per cent of the H_2O in the primitive gas condensed into solids which later formed the Earth. If we take $H \sim 10^6$ as the maximum amount left over from the formation of water-ice in the planetesimals, then we can set the upper limit $N+C \leqslant 3 \times 10^5$ and to order of magnitude $N \lesssim 10^5$, $C \lesssim 10^5$.

In what follows, the primary composition of the planetesimals will be taken to be $H_2O \approx 4 \times 10^6$ plus the oxidized Si-group which can be *formally* represented by $MgSiO_3 \approx 1{\cdot}2 \times 10^6$ and the Fe-group with abundance $0{\cdot}2 \times 10^6$. This corresponds to $x(H) \approx 4$ per cent by mass and $x(H_2O) \approx 35$ per cent by mass. The ratio of oxygen target nuclei to heavier target nuclei is 3 to 1. For the fraction of the neutrons captured by hydrogen, one finds $\sigma_1 H^1/\Sigma = \frac{2}{3}$.

In the above analysis the meteoritic value for $L/\mathrm{Si} = 1{\cdot}44 \times 10^{-4}$ given by SU has been employed. This value leads to $L_s/\mathrm{Si} = 1{\cdot}65 \times 10^{-3}$ and finally to $H^1/\mathrm{Si} = 8$ in the planetesimals. Professor H. C. Urey has informed us privately that he is inclined to question the meteoritic ratio for L/Si. This ratio is based on early measurements which frequently yielded too high values in the case of low abundances. A lower value for L/Si would yield a considerably lower value for H^1/Si. In this case, Urey points out that the irradiation might have occurred after the formation and break-up of lunar sized objects which he has discussed in some detail (Urey 1957). The planetesimals resulting from the break-up consisted of material which has already been fractionated in the lunar sized objects and in particular did not contain large amounts of hydrogen as water or otherwise.

9. Energy and particle flux requirements

In the primitive terrestrial material irradiated by high-energy particles from the condensing Sun, 1650 LiBeB were produced per 10^6 Si nuclei. Relative to 10^6 Si in all of the material after dilution, 165 LiBeB were produced and 144 survived in this group. What total number and energy of charged particles were required to accomplish this? The stopping material in the planetesimals consisted of $H = 8 \times 10^6$, $O = 7{\cdot}5 \times 10^6$, Si-group $= 2{\cdot}5 \times 10^6$, and Fe-group $= 1{\cdot}6 \times 10^5$ relative to $\mathrm{Si} = 10^6$. The density was approximately $1{\cdot}8$ g/cm^3. The high-energy charged particle radiation from the condensing magnetically active Sun consisted primarily (90 per cent by number) of protons along with some He, C, N, O, Ne, etc., in decreasing amounts. We will concentrate on the predominant proton interactions.

The energy of the protons from the Sun and, in fact, the energy per nucleon of all the particles was probably very similar to that of high-energy particles emitted from solar flares at the present time. Meyer, Parker & Simpson (1956) found an integral momentum spectrum for the solar flare of 1956 February 23 proportional to $(pc/Z)^{-n}$ in the range $2 < pc/Z < 20$ BeV where pc is the particle momentum in energy units, Z is the charge. The exponent could not be determined accurately but in any case $3 < n < 7$. Parker (1957) has given a theoretical expression for the integral spectrum in kinetic energy E which will fit this at high energies of the form

$[(E^2/2)+E+1]^{-2}$. The corresponding differential spectrum is proportional to $(E+1)[(E^2/2)+E+1]^{-3}$. In these expressions, E is in units of the nucleon mass energy equivalent ~ 940 MeV. There is some evidence that these expressions hold well below 100 MeV. The differential spectrum drops off steeply at high kinetic energies and has an average value $\bar{E} = 0{\cdot}57$ or 540 MeV.

The number of light nuclei produced by a proton is given by $L_s/p = P_L(1-\exp(-R/\lambda))$ where $\lambda = (\Sigma s_A N_A)^{-1}$ is the mean free path for interaction, $P_L = \lambda \Sigma P_{LA} s_A N_A$ is the LiBeB fragmentation probability averaged over A, s_A is the interaction cross section for a proton with nucleus of mass number A, and R is the range as determined only by energy loss through electron collisions. For N_A in number per gram, the unit for λ is g/cm^2; for N_A in number per cm^3, the unit for λ is the cm. R and λ must be expressed in the same units. The quantities P_L and λ are independent of energy at sufficiently high energies while R varies approximately as $E^{\frac{7}{4}}$. The expression for L_s/p must be integrated over the energy spectrum for the protons. If the interaction cross section is taken to be geometrical, $s_A = \pi R_0{}^2 A^{\frac{2}{3}}$ with $R_0 = 1{\cdot}45 \times 10^{-13}$ cm, then one finds for the mean free path

$$\lambda = \frac{1}{\sum\limits_A s_A N_A} = \frac{25}{\sum\limits_A x_A A^{-\frac{1}{3}}} \text{ g/cm}^2 \tag{35}$$

where x_A = fraction by mass of nuclei of mass number A. The use of the rather large value for R_0 compensates for the neglect of the size of the proton, the range of nuclear forces, and diffraction effects. With the composition given above for stopping material in the primitive chunks of terrestrial matter, on finds $\lambda = 72$ g/cm^2 or ~ 40 cm. The range R varies from zero to much greater than λ over the energy spectrum. Rather than carry out an exact integration we will assume that all protons with $R > \lambda = 72$ g/cm^2 will contribute P_L light nuclei and those for $R < \lambda$ will contribute none. The energy corresponding to a range of 72 g/cm^2 is 330 MeV or $E = 0{\cdot}35$ (Sternheimer 1959) and the number of protons with energy greater than this is $[(E^2/2)+E+1]^{-2} = 0{\cdot}50$. The interaction cross section is ~ 450 mb so $P_L = 90/450 = 0{\cdot}2$. Thus, on the average, protons of energy $\bar{E} = 540$ MeV produce $L_s/p = 0{\cdot}10$ light nuclei. The production of one light nucleus requires $\bar{E}(p/L_s) = 5{\cdot}4$ BeV or $8{\cdot}6 \times 10^{-3}$ ergs.

Since we have predicated part of our basic argument on the assumption that the average meteoritic content of LiBeB is similar to that of the Earth, it is not unreasonable to assume that the same is true for all of the terrestrial planets, Mercury, Venus and Mars, as well as the Earth. The total mass in which 165 light nuclei were produced per 10^6 Si nuclei is thus $1{\cdot}2 \times 10^{28}$ g. The standard element Si constitutes about 18 per cent of this by mass so we are concerned with $4{\cdot}6 \times 10^{49}$ Si nuclei. By the simple proportion, 165 to 10^6, it is then clear that $7{\cdot}6 \times 10^{45}$ LiBeB nuclei were produced in the material of the terrestrial planets. The total number of high-energy protons required was thus $7{\cdot}6 \times 10^{46}$ carrying some $4{\cdot}1 \times 10^{46}$ BeV or $6{\cdot}5 \times 10^{43}$ ergs of energy. As a matter of reference we note at this point that on our approximation one-half of these protons each produced two neutrons while one-half produced none. Thus the total number of neutrons produced and captured was also $7{\cdot}6 \times 10^{46}$.

It will be noted that the energy requirement is only slightly greater than 1 per cent of the energy lost (Section II, 8) in the transfer of angular momentum from the solar condensation to the planetary nebula. Even with a frequency of collision between the high-energy particles and the planetesimals of $\sim$ 10 per cent (Section IV, 1) this will require that only 10 per cent of the available energy be dissipated in high-energy particles. Intense solar flares with total energy outputs of the order of 10^{32} ergs *are observed* to produce relativistic particles with total energy of the order of 10^{31} ergs. During the early active period the Sun emitted $\sim 5\times10^{47}$ high-energy particles carrying $\sim 5\times10^{44}$ ergs in 10^7 years. This is approximately 10^7 times its present rate of high-energy particle production. Only 10 per cent of the particles collided with the planetesimals; the remaining 90 per cent returned along the lines of magnetic force to the Sun.

The inner portions of the solar system probably received substantially the same irradiation. *Extensive observations on isotopic abundances in meteoritic material will be required to reveal any small variations.* On the other hand, the major planets with mass 200 times that of the terrestrial planets experienced at most 5 per cent of the terrestrial irradiation if 10^{45} ergs out of the 5×10^{45} ergs of rotational energy is taken as a maximum for the dissipation in the form of high-energy particles and 100 per cent collisional frequency is assumed.

It will also be clear that the above analysis implies that the high-energy particles from the Sun are not stopped in gas in between the small planetesimals. The gas must not introduce a stopping layer of more than 100 g/cm^2 and at $\rho\sim10^{-9}$ g/cm^3, this permits a total path length of less than 10^{11} cm. We require 10^{13} cm as a minimum to cover the region of the terrestrial planets. Thus, the density must have been reduced to at least 10^{-11} g/cm^3 and more realistically to 10^{-12} g/cm^3 when the irradiation of the planetesimals and the formation of DLiBeB took place. The sweeping out of the gas from the region of the terrestrial planets occurred early in the processes here under discussion. This is quite reasonable since the overall process resulted in the complete removal of most of this gas from the solar system. This conclusion is in line with the ideas of Brown (1952), Suess (1949), and Urey (1957), that the gases were lost by hydrodynamic flow while the Earth's mass was widely dispersed. We would change hydrodynamic to magneto-hydrodynamic.

10. Thermalization of the neutrons

In all the preceding, we have assumed that the neutrons produced in spallation were thermalized and interacted with nuclei long before decaying. It will now be shown that this is the case for the material in the condensed, non-gaseous state. However, in the primitive gaseous state, the situation was quite different.

The time for thermalization and capture of neutrons is given by

$$t \approx \frac{10^{24}}{N_0 v \rho}\left[\frac{1}{\sum(x\xi\sigma_{\text{scat}}/A)}+\frac{1}{\sum(x\sigma_{\text{abs}}/A)}\right]\text{ s} \tag{36}$$

where

ρ = density of the material in g/cm^3.

v = thermal velocity = $2\cdot2\times10^5$ cm/s.

N_0 = Avogado's number = 6×10^{23}.

$\sigma_{\text{scat}}, \sigma_{\text{abs}}$ = neutron scattering, absorption cross sections in barns at thermal energies.

ξ = average logarithmic energy loss per scattering = 1 for H^1, $2/(A+\frac{2}{3})$ for $A > 1$.

x = concentration by mass of the nucleus of mass number A.

In the original solar material this time is determined almost entirely by the hydrogen for which $x = 0{\cdot}75$, $\sigma_{scat} = 20$ barns, $\sigma_{abs} = 0{\cdot}33$ barns, $\xi = 1$. The capture time is much longer than the thermalization time and one finds

$$t \sim \frac{3 \times 10^{-5}}{\rho} \text{ s.} \tag{36'}$$

The time depends upon the density during the irradiation and this in turn depends on the model of the early solar system assumed. In the model used in this paper, we can take it that during the early part of the irradiation the primitive mass of the terrestrial planets, including the original hydrogen and helium, was distributed over a disk-shaped volume extending from the orbit of Mercury to slightly beyond that of the Earth and having a thickness about one-tenth of this distance. The mass was thus about $100 \times 10^{28} = 10^{30}$ g, the volume about 10^{39} cm^3 and $\rho \sim 10^{-9}$ g/cm^3 yielding $t = 3 \times 10^4$ s. This is 30 times the mean lifetime ($\sim 10^3$ s) for neutron decay so very few of the neutrons were captured in the gaseous medium even early in the irradiation. On the model we have used, condensation is necessary not only to separate the solids from most of the hydrogen but also to insure neutron thermalization and capture.

In the condensed planetesimals, the thermalization is still primarily due to the hydrogen since $\xi \sim 2A^{-1}$ but only 67 per cent of the capture is by protons. The thermalization time depends on the nature of the hydrogen bonding somewhat but is short compared to the capture time. The percentage by mass of the hydrogen is 4 per cent and the density is $\sim 1{\cdot}8$ g/cm^3. Using equation (36) it can be shown that $t \sim 3 \times 10^{-4}$ s, which is very small compared to the neutron decay time. This justifies our use of $f_r \approx 1$ in Section III, 5.

It is of interest to estimate the distance over which the neutrons diffuse in thermalizing and interacting in the planetesimals. Here the thermalization plays a more important role because of the higher average velocity from production to thermalization than from thermalization to capture. In water, the root-mean-square thermalization distance for neutrons with initial energies in the 1–10 MeV range is about 14 g/cm^2 while the capture distance is about 7 g/cm^2 (Shapiro 1955). Combining these properly yields an overall diffusion distance of about 16 g/cm^2 or 17 cm in ice.

Diffusion distances in heterogeneous materials are difficult to estimate but values have been given for Al and H_2O with the aluminium volume equal to one-half of that of the water (Shapiro 1955). Such a mixture is 42 per cent water by mass, very close to that in the planetesimals, and Al has scattering and capture cross sections typical of the Si-group. The "age to thermal" is given as $51{\cdot}6$ cm^2 corresponding to a root-mean-square diffusion distance of $(6 \times 51{\cdot}6)^{\frac{1}{2}} \sim 18$ cm. Allowing for some capture distance this corresponds to an overall penetration through approximately 30 g/cm^2 of the planetesimals. The effective range of the primary protons has been given as 72 g/cm^2. Thus, we see that the secondary neutrons stray only a short distance from the primary proton path relative to its length and that the neutrons are largely confined to the volume irradiated by the high-energy particles.

11. DLiBeB produced in the Sun and the T Tauri stars

At the same time that DLiBeB were produced in the primitive planetesimals, these same nuclei were produced in the outer layers of the condensing, magnetically active Sun. We assume that similar processes are occurring now in the T Tauri stars.

The great abundance of hydrogen in the solar material will make the results of the irradiation of the outer layers quite different than for the planetary material. Practically all of the neutrons will be captured by H^1 to form D^2 and the primary abundances of the light nuclei will be in the ratio given in the first rows of Tables 5, A, and 5, B, namely $Li_s^6 : Li_s^7 : Be_s^9 : B_s^{10} : B_s^{11} = 17 : 17 : 12 : 42 : 12$ and $Li_s : Be_s : B_s = 34 : 12 : 54$. Actually, these ratios will be somewhat different in the solar synthesis since CNONe constitute the major spallation parents of LiBeB in this case while O and the Si-group do so in the primitive planetary material. These differences should not be very large, however. More importantly, circulation of the surface material to depths where hydrogen burning occurs will change these primary abundances markedly. This will be discussed in what follows.

The energy required to produce spallation products in the solar surface, the site of the magnetic flares in which acceleration processes take place, can be calculated in a somewhat different manner than in the case of the irradiation of the planetesimals *from the outside*. In the first place, hydrogen and helium are in overwhelming abundance in the solar material and dilute the spallation parents of LiBeB. As a matter of fact, the most important interaction will be the spallation of helium by hydrogen, the possible reactions being

$$
\begin{aligned}
&(a)\ He^4(p, 2p)T^3 - 19{\cdot}8\ \text{MeV};\\
&(b)\ He^4(p, pn)He^3 - 20{\cdot}6\ \text{MeV};\\
&(c)\ He^4(p, d)He^3 - 18{\cdot}4\ \text{MeV};\\
&(d)\ He^4(p, 2pn)D^2 - 26{\cdot}1\ \text{MeV};\\
&(e)\ He^4(p, pd)D^2 - 23{\cdot}9\ \text{MeV};\\
&(f)\ He^4(p, 3p2n) - 28{\cdot}3\ \text{MeV}.
\end{aligned}
$$

The neutrons produced in these processes will be captured by protons to form deuterons so that the deuteron production is zero in case (a), 1 in cases (b) and (c) and 2 in cases (d), (e) (f) respectively. The relative reaction probabilities have not been determined experimentally but (a), (b), and (f) would seem to be the most probable. If it is assumed that these processes are equally probable and the others are neglected than to a good approximation one deuteron will be produced on the average per interaction. Since T^3 decays to He^3, two He^3 nuclei are produced per three interactions. The interaction cross section will be the order of 75 mb and the energy required per spallation will be of the order of 20 MeV when the 2·2 MeV energy release on neutron capture in hydrogen is taken into account. This number can be reduced to 12 MeV per D^2 produced, if (f) is taken as the major process. In this case two deuterons are produced per interaction. The origin alalternative would seem the more probable.

In the solar surface material, He^4 outnumbers CNONe plus the Si, Fe-groups by about $3{\cdot}2 \times 10^9 / 5{\cdot}2 \times 10^7 \sim 60$. The cross sections are in the ratio 75 mb to 450 mb so that the He^4 spallation events outnumber those from the heavier nuclei by a factor of 10. In the spallation of the middle weight nuclei, the cross section for the production of deuterons directly or by neutron capture is 1 000 barns. This result is obtained from Table 7 assuming that all neutrons are captured by hydrogen in solar material. Thus the overall result is that $D/L = (60 \times 75 + 1\ 000)/90 \sim 60$ in the spallation in the solar surface. The energy expended in the spallation of the light nuclei in the direct production of the products is ≈ 50 MeV per event and 2·2 deuterons are effectively produced per event. Thus for both helium and light nuclei 20 MeV is expended per deuteron produced. This corresponds then to 1·2 BeV per light nucleus produced. As long as the abundance of the deuterons and light nuclei remain small we can neglect their destruction in high-energy events.

Much of the above has been introduced because of the second major difference between spallation in the solar material and in the planetary material. In the solar material the energy lost by the high-energy particles in scattering by nuclei and electrons is not actually lost from the medium once complete ionization–recombination equilibrium is attained. Inelastic losses involving gamma rays and pions are also returned to the medium. Neutrino losses are small. The only internal losses are those needed directly to produce the spallation products as discussed in the previous paragraph. One requirement set by this energy budget is that the energy released will be lost only in part by thermal radiation. A major fraction of this energy dissipation is spatially highly concentrated. It could be returned to the magnetic-energy field by twisting of the lines of force by locally driven convection. Trapping of high-energy protons by the lines of force also retains the largest fraction of their energy. Escape of high-energy particles from the solar surface as well as gamma rays, X-rays, light and radio waves will eventually dissipate the available magnetic energy of 5×10^{45} ergs minus that expended in spallation. In addition a portion of the energy, $\sim 10^{45}$ ergs, must be used in spreading the planetary material from $R \approx 3 \times 10^{12}$ to its present distribution in the solar system.

In order to make a quantitative comparison between the energy available and the number of light nuclei produced in the solar surface during its active period (duration $\sim 10^7$ years) we will assume that Be^9 constitutes 12 per cent of the light nuclei. Therefore, 10 BeV $= 1 \cdot 6 \times 10^{-2}$ ergs is expended in all spallation events in which, on the average, one Be^9 nucleus is produced. In Section III, 1 it is noted that $Be/H = 2 \times 10^{-10}$ in the solar surface now. Throughout what depth can this ratio hold assuming no mixing to depths where hydrogen burning occurs? Since $x_H = 0 \cdot 7$ the number of Be nuclei per gram is $8 \cdot 4 \times 10^{13}$ and so the total spallation energy expended was $1 \cdot 35 \times 10^{12}$ ergs per gram. This means that $\sim 2 \cdot 7 \times 10^{45}$ $\Delta M/M$ ergs were required to contaminate a fraction $\Delta M/M$ of the solar mass. We will find in what follows that $\Delta M/M = 10$ per cent is required so that $2 \cdot 7 \times 10^{44}$ ergs were expended in spallation. This is only ~ 5 per cent of the total available magnetic flare energy 5×10^{45} ergs.

If Li has not been depleted since its production in the ratio $Li_s/Be_s = 2 \cdot 8$, we would expect $Li/H = 5 \cdot 6 \times 10^{-10}$ in the Sun now. From the data quoted in Section III, 1 it is actually $Li/H = 0 \cdot 8 \times 10^{-11}$ or $Li/Be = 0 \cdot 04$. On the other hand, the expected value falls in the range $Li/H = 3 \times 10^{-10}$ to 4×10^{-9} observed in the T Tauri stars. These stars have at least ten times as much Li in their surfaces as is found in the nebula surrounding the star from which it presumably condensed. (This primordial nebula is not to be confused with the much smaller scale nebula which formed planets in the case of the Sun.) An immediate explanation of these facts is that the T Tauri stars have produced Li and other spallation products just as the Sun once did and that the solar surface has in addition undergone convective mixing to temperatures and densities necessary to partially burn Li but not Be. Problems arising in connection with the T Tauri stars will be discussed at the conclusion of this section. For quantitative discussion of the hydrogen burning of the light nuclei we list relevant lifetimes as a function of temperature and density in Table 10 based on calculations of Fowler (1954, 1960) and Salpeter (1955).

Table 10

Dependence of log $\tau\rho x$ for various nuclei on temperatures

Nucleus	H^1	D^2	D^2	He^3	He^3	Li^6	Li^7	Be^9	B^{10}	B^{11}
Reaction	$H^1(p, \beta^+\nu)D^2$	$D^2(p, \gamma)He^3$	$D^2(d, n)He^3$	$He^3(He^3, 2p)He^4$	$He^3(\alpha, \gamma)Be^7$	$Li^6(p, \alpha)He^3$	$Li^7(p, \alpha)He^4$	$Be^9(p, d)2He^4$	$B^{10}(p, \alpha)Be^7$	$B^{11}(p, \alpha)2He^4$
			$D^2(d, p)T^3$					$Be^9(p, \alpha)Li^6$		
x	$x(H^1)$	$x(H^1)$	$x(D^2)$	$x(He^3)$	$x(He^4)$	$x(H^1)$	$x(H^1)$	$x(H^1)$	$x(H^1)$	$x(H^1)$
log $S_0 f_0$	−21·43	−4·07	2·04	3·20	−0·12	3·78	2·08	4·58	4·38	5·08
log α	4·94	−12·37	−18·13	−19·26	−15·79	−20·35	−18·65	−21·18	−21·02	−21·71
β	33·80	37·20	42·58	122·76	128·26	84·13	84·71	103·59	120·62	120·95
T_6 = 1	19·61	3·77	0·35	34·05	39·91	16·18	18·13	23·80	31·36	30·81
2	16·78	0·64	−3·25	23·25	28·61	8·84	10·74	14·72	20·75	20·17
3	15·42	−0·86	−4·99	18·02	23·14	5·29	7·17	10·32	15·61	15·02
4	14·58	−1·80	−6·08	14·72	19·69	3·06	4·92	7·55	12·37	11·77
5	13·98	−2·47	−6·85	12·38	17·24	1·47	3·32	5·59	10·07	9·47
8	12·87	−3·70	−8·29	7·99	12·66	−1·48	0·34	1·91	5·77	5·15
10	12·40	−4·22	−8·88	6·14	10·72	−2·72	−0·91	0·36	3·95	3·33
15	11·66	−5·05	−9·85	3·13	7·57	−4·75	−2·95	−2·15	1·00	0·36
20	11·20	−5·57	−10·46	1·24	5·59	−6·02	−4·23	−3·74	−0·85	−1·49
30	10·63	−6·20	−11·20	−1·12	3·11	−7·61	−5·83	−5·72	−3·18	−3·82
40	10·28	−6·60	−11·66	−2·60	1·56	−8·60	−6·83	−6·96	−4·63	−5·28
50	10·03	−6·87	−11·99	−3·66	0·45	−9·30	−7·53	−7·84	−5·67	−6·32

$$\tau\rho x = \alpha T_6^{2/3}(1 - 5T_6^{1/3}/12\beta)\exp(\beta/T_6^{1/3})$$

$$\log \tau\rho x = \log \alpha + \tfrac{2}{3}\log T_6 - 0{\cdot}18T_6^{1/3}/\beta + 0{\cdot}434\beta/T_6$$

τ = mean life-time in years of nucleus with mass number A_0, charge number Z_0.
ρ = density in g/cm³.
x = concentration by mass of reacting atom with mass number A_1.
T_6 = temperature in 10^6 °K.
S_0 = low-energy cross section constant for reaction indicated in keV-barns for centre-of-mass system.
f_0 = low-energy electron shielding factor $\approx \exp(0{\cdot}058\, Z_1Z_0)$.
$\alpha = A_1(A/Z_1Z_0)^{1/3}/(7{\cdot}83\times10^8\times3{\cdot}16\times10^7\, S_0f_0)$.
$\log\alpha = -16{\cdot}39 - \log S_0f_0 + \log A_1 + \tfrac{1}{3}\log(A/Z_1Z_0)$ with $A = A_1A_0/(A_1+A_0)$.
$\beta = 42{\cdot}48\,(AZ_1^2Z_0^2)^{1/3}$.

Recent calculation on the extent of the convective zone in the primitive and the present Sun quoted by Schwarzschild (1958, Tables 28.3 and 28.6) indicate that the zone has not extended through more than 0·2 per cent of the mass of the Sun or down to more than $T \sim 1 \times 10^6$ °K since the Sun was stabilized by hydrogen burning in its centre. At this temperature both Li isotopes have very long lifetimes. Thus, if long-period convection and diffusion are neglected, we must assume that the deep mixing occurred just as the Sun settled onto the main sequence and after the active period at $R \sim 3 \times 10^{12}$ cm. As the Sun settled onto the main sequence, convective mixing to at least $T \sim 10^6$ °K and $\rho x_H \sim 10^{-2}$ g/cm^3 occurred and this temperature and density were quite sufficient to initiate rapid burning of the deuterium previously produced during the active period. The lifetime of deuterium in the process $D^2(p, \gamma)He^3 + 5{\cdot}5$ MeV is approximately 10^6 years under these conditions according to Table 10. From our previous discussion $D/L = 60$, $L/Be = 8$, $Be/H = 2 \times 10^{-10}$ so $D/H = 10^{-7}$. Thus $\sim 4 \times 10^{16}$ deuterons were available per gram and $\sim 4 \times 10^{11}$ erg/g resulted from the deuterium burning. Expended in the surface layers in a short time interval, this energy may well have induced deeper mixing so that Li was also consumed. McKellar (1960) quotes $D/H < 4 \times 10^{-5}$ in the Sun now.

In Section III, 1, the ratio $R = Li^6/Li^7$ in the Sun is observed to fall in the range 0·05 to 0·5 with $R = 0{\cdot}14$ being given by the observed mean wave length for the blended line. We use this latter value for definiteness. Then we find $Li^6/Be^9 = 0{\cdot}005$ and $Li^7/Be^9 = 0{\cdot}035$ in the Sun and these values are to be compared with the estimated primary spallation ratios of $Li_s{}^6/Be_s{}^9 = Li_s{}^7/Be_s{}^9 = 1{\cdot}4$. The depletion factor is thus 280 for Li^6 and 40 for Li^7 relative to Be^9 and 7 for Li^6 relative to Li^7. From Table 10, it will be clear that Li^6 is burned approximately 70 times faster than Li^7 at all relevant temperatures. If we agree to retain $R \sim 0{\cdot}14$ and in any case $R > 0{\cdot}05$, we must then assume that the Li^6 depletion was controlled by the mixing time rather than its short life time. Let the mean mixing time determined by convection be t_c. For simplicity, assume that the mixing carries the material for a fraction f of this mixing time to a region in which ρ and T are such that a given nucleus has lifetime τ. This region will be the bottom of the convective layer above which the lifetime is relatively very long. Then after a total time t the abundance will be given by

$$\ln \frac{N(t)}{N(0)} = -\frac{t}{t_c}\left(1 - \exp\left(-\frac{ft_c}{\tau}\right)\right)$$
$$\to -t/t_c \qquad \tau < ft_c$$
$$\to -ft/\tau \qquad \tau \gtrsim ft_c. \tag{37}$$

In Section II, 3 we have given the Kelvin–Helmholtz time for the contraction of the Sun onto the main sequence as 3×10^7 years. The total time, t, available for convection and Li-burning will be of this order of magnitude. For Li^6, take $\tau < ft_c$ so that $t_c/t = (\ln 280)^{-1}$ or $t_c = 5{\cdot}4 \times 10^6$ years, a not unreasonable value. With t and t_c both given, we then find for Li^7 that $[1 - \exp(-ft_c/\tau_7)] = 3{\cdot}7/5{\cdot}6 = 0{\cdot}66$ so that $\tau_7 = 0{\cdot}9 ft_c$. For a reasonable choice of f, say $\frac{1}{8}$, we then find $\tau_7 \sim 10^6$ years. From Table 10, this occurs at $T = 3{\cdot}4 \times 10^6$ °K and $\rho x_H \sim 2$ g/cm^2. The Li^6 lifetime is $\sim 10^4$ years, fulfilling the condition used above, while the Be^9 lifetime is $\sim 10^9$ years under these conditions, indicating very little depletion. According to Table 28.3 in Schwarzchild (1958), these ρ, T conditions occur below $\Delta M/M = 10$ per cent in the primitive Sun. Thus we have substantiated the statement made above that only 5 per cent of the total available magnetic flare energy was needed to produce DLiBeB in the fraction of the solar mass involved. Even this requirement can be lowered if Hoyle's minimum estimate for the rotational energy dissipated is revised upward and if the energy requirements per light nucleus are made in a more optimistic manner than in previous paragraphs. In any case, we see qualitative reasons for the depletion of Li to a small but non-zero value while not depleting Be at all: the time scale for the final contraction was several times the Li^7 lifetime under the temperature–density conditions to be expected in a convective zone of reasonable extent but was very short compared to the lifetime of Be^9; furthermore, a reasonable value for the mixing time relative to the total time permitted the survival of a small fraction of the otherwise rapidly consumed Li^6.

We note at this point that He^3 is not depleted at all by $He^3(He^3, 2p)He^4$ or $He^3(\alpha, \gamma)Be^7$ under the conditions described above (see Table 10) so that all the primary spallation He^3 and that from $D^2(p, \gamma)He^3$ should remain in the outer surface of the Sun. Adding the two contributions yields $He^3/H^1 \approx 3 \times 10^{-7}$ or $He^3/He^4 \approx 3 \times 10^{-6}$. Present techniques are only sensitive enough to indicate $He^3/He^4 < 0{\cdot}03$. Magnetic activity of the Sun since it settled on the main sequence may have enhanced He^3/He^4 considerably. The He^3/He^4 ratio could be considerably higher in stars which are much more magnetically active than the Sun and which have much thinner convective layers. The layer must be deep enough to reach the temperature ($\sim 10^6$ °K) necessary to promote $D^2(p,\gamma)He^3$. Then every neutron produced by magnetic activity and associated high-energy processes in the stellar surface eventually produces He^3, through the chain $H^1(n, \gamma)D^2(p, \gamma)He^3$ Burbidge, Burbidge & Fowler (1958) estimated $He^3/He^4 \sim 1$ in active stars. Appa Rao (1961) has recently reported $He^3/He^4 \sim 0{\cdot}7$ in low-energy cosmic rays.

We also note that $B/Be = 4{\cdot}5$ or $B/H = 9 \times 10^{-10}$ is to be expected in the Sun and T Tauri stars and that Li^6 might still be quite comparable to Li^7 in the T Tauri stars where Li : Be : B = 34 : 12 : 54 is our best estimate. For these conclusions to be true it is required that Li-burning not have commenced at all in the T Tauri stars. When it does, Li^6 will be the first to decrease appreciably in abundance. Unfortunately, rotational broadening of lines, and low resolution prevent accurate measurement of wave lengths, and therefore of the Li^6/Li^7 ratio in the T Tauri stars.

Predictions concerning the composition of the "cosmic" rays from solar flares cannot be made in any simple manner. This is because the acceleration mechanism may not be independent of charge or mass and because spallation products and neutrons will be produced in copious quantities in the flare material during the acceleration processes. Thus the material changes composition markedly as the flare proceeds.

12. Production of other light nuclei

In this Section consideration is given to the production of various light nuclei in the mass number range $12 < A < 40$ through the operation of the primary spallation and secondary neutron interactions in the planetesimals. Discussion of the light noble gases He, Ne, and A is not attempted here but is postponed to Section III, 15. The spallation cross sections and overall yields relevant to the discussion are included in Table 7.

Carbon produced by spallation processes will be retained in the planetesimals. Table 7 gives an estimate for the overall yield of C^{13}, namely $C^{13} = 33$ relative to $Si = 10^6$. No estimate has been made for C^{12} but it will not exceed this value by more than a factor of 3. However, $C^{12}/C^{13} = 90$ in terrestrial carbon. Thus, if no subsequent separation of spallation carbon from primitive carbon occurred, a lower limit on the carbon which condensed in the planetesimals can be established, namely $C \sim C^{12} \gtrsim 3 \times 10^3$. The limiting value is the same as the value quoted for the terrestrial–meteoritic abundance of C, namely 3×10^3, given in Table 2 and due to Goldschmidt (1937). It can therefore be argued that it is possible for all terrestrial C^{13} to be due to the early irradiation of the material of the solar system and that little C^{13} existed in the primitive solar material.

The conclusion that terrestrial C^{13} was produced by spallation processes in the intermediate planetesimal stage implies that C^{13}/C^{12} should be considerably less in the Sun than in terrestrial material where $C^{13}/C^{12} = 1/90$ as indicated above. The spallation yield of C^{13} in the Sun is certainly small compared to the observed $C = 1 \cdot 7 \times 10^7$. Greenstein, Richardson & Schwarzchild (1950) found no lines corresponding to known isotope doublets of $C^{13}N^{14}$ in the solar spectrum and set a conservative upper limit $C^{13}/C^{12} \leqslant 1/36$. Righini (1956) found a very weak spectral feature which he attributed to C^{13} and was able to set $C^{12}/C^{13} \approx 4000$ with a maximum uncertainty of a factor of 3. The observational data is thus consistent with the conclusion reached above.

The argument can be carried somewhat further. According to B^2FH (1957) the nucleus C^{13} is produced in stars in hydrogen burning through the operation of the CNO-cycle on C^{12} and O^{16}. These last two nuclei, along with Ne^{20}, are produced in helium burning in red giant stars. After ejection from such stars and mixing with interstellar hydrogen, these nuclei can be incorporated in stars which form at a later time. The CNO-cycle is also the source of N^{14} and O^{17}. The effective site of the cycle is the high-temperature shell in which hydrogen burning occurs as a helium core develops. Using the cross section data of Fowler (1960), the equilibrium abundances in the CNO-cycle at 35×10^6 °K are estimated to be

$$C^{12}:C^{13}:N^{14}:N^{15}:O^{16} = 0{\cdot}024:0{\cdot}006:0{\cdot}95:4 \times 10^{-5}:0{\cdot}02 \qquad (38)$$

Experimental data on the $O^{17}(p, \alpha)N^{14}$ cross section are not yet available. Rough theoretical estimates indicate that the production of O^{17} will be quite small and so it is not included in equation (38). Thus the CNO-cycle essentially converts C^{12} and O^{16} into N^{14} and small amounts of C^{13}, N^{15}, and O^{17}. (*Note added in proof:* For an updated discussion using new $O^{17}(p, \alpha)$ N^{14} data see Brown (1961) and Caughlan & Fowler (1961). The temperature at which the CNO-cycle seems to have operated is found by Brown to be $\sim 20 \times 10^6$ °K. The argument to follow is not essentially changed, however.)

The high equilibrium abundance of N^{14} and of C^{13} in the CNO-cycle are not detected at the surface of the Sun, nor even in stars in which stellar evolution is more advanced and more violent. Thus old novae, planetary nebulae and B supergiants are objects in which hydrogen has been largely converted to helium, and in which N^{14} should be very abundant. Yet in none of these are radical alterations in the H/He or C/N ratio detected. Only in a few "stumps" of burnt-out stars are the He/H and N/C ratios greatly changed. We conclude, therefore, from observations, that for many types of stars and certainly for the Sun, the efficiency and rate of mixing between the surface and the energy-producing cores is very low, and that for the primeval Sun it was zero.

Let β represent the original production ratio of O^{16} relative to C^{12} in helium burning and let f represent the fraction of C^{12} and O^{16} which has been processed in the CNO-cycle. Then with considerable generality, it is possible to write

$$\begin{aligned} C^{12}:N^{14}:O^{16} &= 1-f+0{\cdot}024f(1+\beta):0{\cdot}95f(1+\beta):\beta(1-f)+0{\cdot}02f(1+\beta) \\ &= 5{\cdot}5:1:9{\cdot}6. \end{aligned} \tag{39}$$

The last numerical values are the solar abundances ratios given by GMA (1960). Solution of (39) for the two unknowns yields $\beta = 1{\cdot}75$ and $f = 1/15$. This last result indicates that only a small fraction of the C^{12} and O^{16} originally destined for the Sun was processed in the CNO-cycle in intermediate stars. This result is consistent with the fact that $Ne^{22}/Ne^{20} = 1/9$ terrestrially, and presumably in the Sun, in spite of the fact that Ne^{20} produced in helium burning is converted in large measure into Ne^{22} in hydrogen burning. The fact that only small fractions of C^{12}, O^{16} and Ne^{20} are reprocessed in stars has important implications in regard to stellar evolution in the galaxy. For our present purposes, we see that C^{13} and N^{15} should be quite rare in the Sun. Using the production rates relative to N^{14} as given in equation (38), one finds from the GMA ratios in equation (39) that $C^{13}/C^{12} = 10^{-3}$, and $N^{15}/N^{14} = 4\times10^{-5}$. It will be noted that this calculated C^{13}/C^{12} ratio is consistent with the observational data discussed in the previous paragraph. There is no necessary contradiction in that this solar ratio is only one-tenth of the terrestrial ratio since it has been shown that spallation production in the planetesimals may well account for terrestrial C^{13}.

Nitrogen produced by the irradiation probably escaped from the planetesimals although some N^{15} may have replaced original N^{14} in such compounds as NH_4Cl and TiN. If spallation nitrogen did not escape, then from the spallation yield $N^{15} = 90$ in Table 7 and the terrestrial ratio $N^{14}/N^{15} = 275$ it follows that $N \gtrsim 2{\cdot}5\times10^4$ as the original abundance in the planetesimals. This is much greater than the estimated meteoritic–terrestrial value $N \sim 25$ given in Table 2. We are inclined to believe that very little nitrogen condensed in the planetesimals and that most of the spallation yield escaped before combining chemically. If 10 per cent of the Cl given by SU (1956) condensed as NH_4Cl and if most of the N was in the form of NH_4Cl then $N \sim 10^3$ in the small planetesimals. This would seem a reasonable value for nitrogen but definitely implies that most of the spallation N escaped while the chemically combined N did not. In the CNO-cycle, $N^{15}/N^{14} = 4\times10^{-5}$ as indicated above, so this cycle is not an adequate source of N^{15}. On the other hand, if only 4 per cent of the spallation yield replaced the N^{14} in the combined nitrogen then $N^{14}/N^{15} = 1\,000/(90\times0{\cdot}04) \approx 280$ and the terrestrial ratio is accounted for. It seems reasonable then that terrestrial N^{15}, as well as C^{13}, was produced by irradiation of the small planetesimals. Inspection of the last two columns of Table 7 yields the conviction that this was not the case for O^{17}, O^{18}, or F^{19}. The production of O^{18} and F^{19} in helium burning has been discussed by B^2FH (1957). An understanding of O^{17} production requires experimental data on the $O^{17}(p, \alpha)N^{14}$ cross section (see references in *Note* on p. 190).

Turn now to nuclei of intermediate mass number. Radioactive nuclei produced by irradiation in this region include Al^{26} with $\bar{\tau} = 1{\cdot}0\times10^6$ years and Cl^{36} with $\bar{\tau} = 4{\cdot}4\times10^5$ years. Table 7 indicates overall yields of $Al^{26} = 28$ and $Cl^{36} = 90$ in the small planetesimals which eventually formed the Earth. It will be noted that most of the Cl^{36} is produced via $Cl^{35}(n, \gamma)$ for which the thermal cross section is $33{\cdot}6$ barns so that $\Delta Cl^{35}/Cl^{35} = 33{\cdot}6\times4\times10^{-4} = 1{\cdot}3$ per cent after irradiation and dilution. (See Section III, 13 for discussion of the method of calculation.) With Cl^{35} = 6 700 given by SU (1956), one finds $Cl^{36} \approx 90$ as indicated in Table 7. The Al^{26} = 28 comes from such reactions as $Mg^{26}(p, n)Al^{26}$, $Al^{27}(p, pn)Al^{26}$, and $Si^{28}(p, 2pn)Al^{26}$. The irradiation period has been taken as 10^7 years so at the end of this period Al^{26} = 2·8 and Cl^{36} = 4 after multiplication by $\bar{\tau}/10^7$.

These short-lived radioactivities have been considered by Fish, Goles & Anders (1960) as possible sources of energy in planetesimals of asteroidal dimensions (~250 km) which, on their point of view, served as parent bodies of the meteorites. These authors require a heat input into these planetesimals of the order of 10^{-4} cal g^{-1} $year^{-1}$. Their calculations indicate initial heat outputs of $1{\cdot}4 \times 10^{-3}$ cal g^{-1} $year^{-1}$ for Al^{26} = 2·8 on the Si = 10^6 scale and 5×10^{-4} cal g^{-1} $year^{-1}$ for Cl^{36} = 4. Clearly, Al^{26} is the more effective. With this radionucleus as the heat source, it is required that the large planetesimals formed from the small planetesimals within a few mean lives or several millions of years. If the small planetesimals underwent irradiation until incorporated in the large ones, it will be seen that this time scale actually need apply only to the latter part of the growth of the large planetesimals. Once these objects reached a fairly large collision area, further rapid growth does not seem improbable. In any case, our point of view removes the necessity of producing large objects in the solar nebula within a few million years of the last event of *galactic* nucleosynthesis. Last minute synthesis in the solar nebula will suffice. Rome was not built in a day!

13. General effects of planetesimal irradiation on heavy nuclei

Among the heavy nuclei the most interesting effects of the irradiation of the primitive material of the solar nebula would seem to be the anomalies recently discovered in meteorites involving the isotopes of Xe (Reynolds 1960, abcd) and Ag (Murthy, 1960). Before discussing these anomalies, the general effects of spallation and neutron irradiation on heavy nuclei must be discussed.

For spallation yields not listed in Table 7, the following estimates can be made especially for the heavier nuclei. Before dilution of irradiated material by shielded material, terrestrial matter contained 1 650 light nuclei per 10^6 Si-nuclei. The actual target nuclei for spallation number 10^7 *in toto* if O^{16}, the Si-group, and the Fe-group are combined. The fragmentation probability for light nucleus production is P_L = 0·2 so 5 spallation events occurred per light nucleus produced. The number of spallation events per target nucleus was thus $\sim 0{\cdot}8 \times 10^{-3}$. After dilution this number was reduced to $0{\cdot}8 \times 10^{-4}$ per nucleus in the planetesimals. The spallation cross section varies as $A^{\frac{2}{3}}$ and for O/Si-group ~ 3 one finds $\langle A^{\frac{2}{3}} \rangle \approx 7$. Thus for nuclei of mass number A, the spallation depletion will be, to sufficient accuracy, equal to $A^{\frac{2}{3}} \times 10^{-5}$. For the energy spectrum characteristic of solar flares most of the spallation events will result in the removal of only a few neutrons, protons, and alpha particles so that each heavy nucleus will produce about $A^{\frac{2}{3}} \times 10^{-5}$ of its abundance in new heavy nuclei just below it in mass number. For example, for A = 125, the fractional production is $2{\cdot}5 \times 10^{-4}$. This fraction is the overall result of the spallation and dilution of the primitive terrestrial material. The new nuclei will tend to be on the neutron deficient side of the mass valley and will be spread over a range of mass numbers equal to about 15 per cent of the mass number of the parent nucleus. It will be clear that in any region of mass numbers, the nuclei of "normal" abundance will not be affected by the spallation in a detectable way. However, the rare, neutron-deficient, light isotopes of the heavy elements might be expected to reveal consequences of the early irradiation. This will prove to be the case for the two light isotopes of Xe.

Our calculations will assume that the spallation decrement for any given nucleus with mass number A is $A^{\frac{2}{3}} \times 10^{-5}$ of its own abundance and that the spallation increment is $A^{\frac{2}{3}} \times 10^{-5}$ of the *average* abundance of the nuclei with mass numbers $A+1$ to $\sim 1{\cdot}15A$ excluding those with atomic number Z less than that of the nucleus in question. (Negative pion emission is taken to be small.) In keeping with the discussion in Section III, 5 we assume that the figure 10^{-5} applies to the material of the meteorites and the terrestrial planets. In general, we can write

$$\Delta N_A = -\frac{Y_s}{F_d} A^{\frac{2}{3}} \left(N_A - \frac{\gamma_I}{A'-A} \sum_{A+1}^{A'} N_A \right) \quad \text{for} \quad (Y_s \ll 1). \tag{40}$$

In this equation, N_A represents the original abundance of a given nucleus in the planetesimals and $N_A + \Delta N_A$ is the abundance after irradiation and dilution. In order to retain a simple notation, A represents the pair of variables, A, Z, necessary to completely identify a given nucleus. In calculating ΣN_A the abundance of *all* isobars at A must be summed in computing the contribution from a given A excluding those with atomic number Z less than that of the nucleus in question. The calculations are not very sensitive to the choice of A' but we have taken A' as the integer closest to $1{\cdot}15A$. The cross section variation over $A'-A$ has been neglected. The quantity γ_I indicates that the spallation yield must be divided among the various isobars at A. For only one stable isobar $\gamma_I = 1$. For two or three isobars, the situation is complicated and little experimental information is available. In general, neutron deficient isobars are favoured in spallation as long as they are not too far from the general line of stable nuclei. Y_s is proportional to the spallation yield and F_d is the dilution factor. For terrestrial matter $Y_s/F_d = 10^{-5}$.

For the neutron capture effects, the general expression for the change in abundance of mass number A can be written as

$$\Delta N_A = -\frac{N_A}{F_d}\left[1 - \exp\left(-\frac{\sigma_A n_r}{\Sigma}\right)\right] +$$

$$+ \frac{N_{A-1}}{F_d}\left(\frac{\sigma_{A-1} n_r}{\Sigma}\right) \exp\left(-\frac{\sigma_A n_r}{\Sigma}\right) \int_0^1 \frac{N_{A-1}(n_r')}{N_{A-1}} \exp\left(\frac{\sigma_A n_r'}{\Sigma}\right) d\left(\frac{n_r'}{n_r}\right). \tag{41}$$

In this expression n_r is the total number of neutrons which interact and n_r' is the corresponding running variable during irradiation. $N_{A-1}(n_r')$ represents the functional dependence of the abundance of $A-1$ on n_r' with $N_{A-1} = N_{A-1}(0)$. It may decrease or increase depending on the solution of an equation for ΔN_{A-1} similar to (41). In the special case that $N_{A-1}(n_r')$ remains substantially constant during irradiation one finds:

$$\Delta N_A = \frac{1}{F_d}\left(\frac{\sigma_{A-1}}{\sigma_A} N_{A-1} - N_A\right)[1 - \exp(-\sigma_A n_r/\Sigma)] \quad \text{for} \quad N_{A-1}(n_r') \approx N_{A-1}. \tag{41'}$$

In case $\sigma_A n_r/\Sigma$ is small compared to unity, this becomes:

$$\Delta N_A = (\sigma_{A-1} N_{A-1} - \sigma_A N_A)\frac{n_r}{F_d \Sigma} \quad \text{for} \quad \sigma_A n_r/\Sigma \ll 1. \tag{41''}$$

In principle, equation (40) should have been written in the form similar to (41). However, no case for large Y_s has come to our attention and so the form of (40), which corresponds to (41″), suffices. The total N_A will be the sum of the ΔN_A given by equations (40) and (41″) for $Y_s < 1$ and $\sigma_A n_r/\Sigma < 1$. If these conditions are not satisfied, a more general relation must be used (see Appendix, equation A17).

In equation (41) it is assumed that radioactivity, if any, of the nucleus produced through neutron capture by $A-1$ has a short lifetime compared to that for neutron capture. The expression can be easily generalized (see Appendix, equation A17) for long lifetimes and for more complicated situations including neutron induced particle emission, etc. For a nucleus which is not produced by neutron capture but is depleted, the fractional depletion is given by

$$\frac{\Delta N_A}{N_A} = -\frac{1}{F_d}[1-\exp(-\sigma_A n_r/\Sigma)] \tag{42}$$

$$\approx -\frac{\sigma_A}{F_d}\frac{n_r}{\Sigma} \qquad \text{for } \sigma_A n_r/\Sigma \ll 1 \tag{42'}$$

$$\approx -\frac{1}{F_d} \qquad \text{for } \sigma_A n_r/\Sigma \gg 1 \tag{42''}$$

The last expression shows that no nucleus will be depleted by more than $1/F_d$ of its original abundance. For terrestrial matter, it has been found that $F_d = 10$ and $n_r/\Sigma = 4\times 10^{-3}$ for σ in barns, so that $(F_d-1)/F_d = 90$ per cent and $n_r/F_d\Sigma = 4\times 10^{-4}$. Thus a one barn capture cross section produces a depletion of 0·04 per cent but the maximum possible depletion is 10 per cent. The abundances of nuclei with large cross sections are sensitive to F_d but not to n_r/Σ. It should be strongly emphasized that outer portions of the solar system did not experience irradiation and dilution characterized by these values.

14. Anomalous isotopic abundances in meteorites: Ag^{107}/Ag^{109}

With equations (40), (41), and (42) established, it is now possible to discuss the anomalous abundances recently discovered in meteorites involving the isotopes of Xe and Ag. The Ag case involves only two isotopes and has a considerably simpler explanation from our point of view and will be discussed first.

Murthy (1960) found $Ag^{107}/Ag^{109} = 1{\cdot}097 \pm 0{\cdot}002$ in Toluca troilite and $Ag^{107}/Ag^{109} = 1{\cdot}074 \pm 0{\cdot}002$ in terrestrial Ag. Thus Ag^{107} is in excess in Toluca troilite by $\sim$ 2 per cent. He attributed the excess Ag^{107} in Toluca to the decay of Pd^{107} ($\bar{\tau} = 1{\cdot}0\times 10^7$ years) trapped in the meteoritic material when it formed some time after the last event of nucleosynthesis. He found this time to be several half-lives of Pd^{107} or more precisely $8{\cdot}4\times 10^7$ years on a "sudden nucleosynthesis" model and $4{\cdot}5\times 10^7$ years on a model of "continuous nucleosynthesis" in the galaxy suggested by Wasserburg, Fowler & Hoyle (1960). The required time interval is thus less than 10^8 years.

Such a short time interval would seem to be quite unreasonable if the synthesis is attributed solely to galactic processes. The interval must cover the time required for uniform mixing in the galaxy, for the separation of the solar system material from galactic material, for the condensation of the Sun and for the formation of the parent bodies of the meteorites. The time required for only the first of these steps is customarily estimated to be at least 2×10^8 years, the period of rotation of the galaxy. It will be noted that Pd^{107} decays to 2×10^{-9} of its original abundance in 2×10^8 years.

An alternative possibility lies in the early irradiation of solar system matter which has been under discussion. The ~ 2 per cent excess Ag^{107} in Toluca cannot be understood on the basis of direct spallation since these effects are at most of the order of 0·02 per cent for nuclei of normal abundance and it is necessary to look to neutron capture effects. The Ag isotopes are produced by neutron capture effects in Pd^{106} and Pd^{108} respectively. Cd^{106} and Cd^{108} have too low abundances to contribute substantially to Ag^{107} and Ag^{109}. The case of Ag^{107} is complicated by the fact that $Pd^{107}(\beta^- \nu^*)Ag^{107}$ has the relatively long lifetime previously mentioned. Nothing is known concerning the thermal cross section for $Pd^{107}(n, \gamma)Pd^{108}$ but unless it exceeds 400 barns, Pd^{107} decays before it captures a neutron. It will be asumed that Pd^{107} always decays. The thermal neutron cross section for elemental Pd is 8 barns and that for Pd^{108} is 10 barns. The cross section for Pd^{106} has not been measured but it cannot exceed 20 barns from the elemental cross section and the known isotopic abundances so it will be assumed to have the same cross section as Pd^{108}. Both are even Z, even N nuclei. The cross section for Ag^{107} is 31 barns and that for Ag^{109} is 87 barns. The relevant isotopic abundances are $Pd^{106} = 0{\cdot}272$ Pd, $Pd^{108} = 0{\cdot}267$ Pd, $Ag^{107} = 0{\cdot}515$ Ag, and $Ag^{109} = 0{\cdot}485$ Ag in terrestrial material. The primitive solar system ratio, Pd/Ag = 3·6 is taken from Clayton & others (1961). The empirically adjusted r and s process abundances of these authors have been added together to give the total abundances.

It will be clear from the data given that both Ag^{107} and Ag^{109} were depleted by neutron irradiation in the early planetesimals, Ag^{109} more so than Ag^{107}. Ag^{109} is the simpler case for the reason already noted above and will be calculated first.

The small cross section for Pd^{108} insures to a sufficient approximation that it remains substantially constant during the irradiation so equation (41′) can be employed. The depletion of terrestrial Ag^{109} relative to primitive solar system Ag^{109} becomes

$$\frac{\Delta Ag^{109}}{Ag^{109}} = \frac{1}{10}\left(\frac{10}{87} \cdot \frac{0{\cdot}267\,\mathrm{Pd}}{0{\cdot}485\,\mathrm{Ag}} - 1\right)[1 - \exp(-87 \times 4 \times 10^{-3})] = -2{\cdot}3 \text{ per cent.} \tag{43}$$

The depletion is small enough that the use of terrestrial isotopic abundances on the right-hand side of equation (43) contributes no appreciable error. A similar calculation for Ag^{107}, taking the Pd^{107} decay as rapid for the moment, yields $\Delta Ag^{107}/Ag^{107} \approx -1$ per cent. The differential depletion of Ag^{109} relative to Ag^{107} is about one-half of the depletion in Toluca troilite relative to the terrestrial isotope abundances. Thus a possible explanation is that the Toluca material received *several times* more irradiation in the planetesimal stage than did the terrestrial material. However, the approximate equality of the D/H ratio in meteorites to that on the Earth makes this very unlikely. Moreover, in view of the time delay introduced by the Pd^{107} decay, it is not necessary to assume this and we turn now to the original suggestion of Murthy in the context of the general theme of this discussion.

In his explanation Murthy points out that Pd/Ag $\sim$ 50 in the Toluca iron meteorite and that a fractionation of Ag from Pd in the formation of the iron is not unexpected on general grounds. He comments: "If the formation of the metal phase of meteorites happened within a few half-lives of Pd^{107} after the end of nucleosynthesis, because of the above mentioned fractionation between Pd and Ag, the metallic phase is likely to show an enrichment of Ag^{107} as a result of the decay of Pd^{107}." We estimate an interval of $6{\cdot}5 \times 10^7$ years for the case of sudden nucleosynthesis. Little radiogenic Ag^{107} is expected in the case of continuous synthesis in the stars of the galaxy. If the "nucleosynthesis" occurred in the small planetesimals then it is required to calculate the Pd^{107} remaining at the end of the irradiation period of 10^7 years. As in the case of Pd^{108} it can be assumed that Pd^{106} was not seriously depleted by the neutron process and in fact it may have been enhanced by the contribution from $Pd^{105}(n, \gamma)Pd^{106}$. Assuming no appreciable change in Pd^{106} and assuming no Pd^{107} remaining from galactic nucleosynthesis, the Pd^{107} at the end of planetesimal irradiation will be given by an equation analogous to equation (41′) (see appendix, equation A17) as follows:

$$Pd^{107} = \frac{Pd^{106}}{F_d}\frac{n_r\sigma_{106}}{\Sigma}\frac{\bar{\tau}}{T}[1 - \exp(-T/\bar{\tau})] \tag{44}$$

$$= 2{\cdot}7 \times 10^{-3}Pd^{106} = 7{\cdot}4 \times 10^{-4}Pd = 0{\cdot}035Ag = 0{\cdot}068Ag^{107}$$

so that

$$Ag^{107*} = Pd^{107}\exp(-\Delta t/\bar{\tau}) = 0{\cdot}075Ag^{107}\exp(-\Delta t/\bar{\tau}). \tag{44′}$$

In the numerical evaluation, $n_r/F_d\Sigma = 4 \times 10^{-4}$ characteristic of terrestrial material has been employed along with $\bar{\tau} = 1{\cdot}0 \times 10^7$ years and $T = 10^7$ years, the period of irradiation. Pd^{107} in an amount equal to 6·8 per cent Ag^{107} remains after irradiation; only 2 per cent is required. Thus, if the material of the meteortite and of the Earth received the *same* irradiation in the planetesimal stage, it was only necessary that the parent body of the meteorite form within one Pd^{107} mean lifetime of the irradiation. This permits an interval as long as 10 million years—somewhat longer than in the case of Al^{26} previously discussed. The Al^{26} may well have supplied the heat energy which eventually resulted in the differentiation processes in those parent bodies which fractionated Pd relative to Ag. We will find in Section III, 15 that the establishment of the I/Xe ratio in meteoritic material required even a longer interval, $\sim 6 \times 10^7$ years. It is not at all unreasonable that the Xe abundance was the last one, of those under discussion, to be finally established in meteoritic material. The important conclusion is that the formation of larger bodies in the solar system did not necessarily follow shortly after a "last event" of galactic nucleosynthesis or after the "first event" of universal nucleosynthesis. The short interval required was a natural and reasonable one in the early history of the solar system itself.

Two explanations have been suggested in the above discussion. One involves greater depletion of Ag^{109} in primitive meteoritic material because of greater irradiation than was the case for primitive terrestrial material. The second, following Murthy, involves enhancement of Ag^{107} in the meteoritic material by Pd^{107} decay following fractionation of Ag relative to Pd. Murthy's explanation would seem to be preferred on the grounds of simplicity as long as the point of view is accepted that the short-lived activities which were incorporated in solar system bodies were produced in the solar nebula itself rather than in galactic processes.

In contrast to the observation of radiogenic Ag^{107} just discussed, Ander & Stevens (1960) failed to find radiogenic Tl^{205} from the decay of Pb^{205} ($\bar{\tau} = 3{\cdot}5 \times 10^7$ years) in various meteorites in which the Pb/Tl ratios differed by factors of as much as 50. In principle, this sets a lower limit to the time interval Δt between the end of nucleosynthesis and the final establishment of the Pb/Tl ratio in meteoritic material. Pb^{205} is produced by neutron capture in Pb^{204} which has a thermal cross section of 0·7 barns. Thus, the amount of Pb^{205} produced during the irradiation of the planetesimals is $2 \cdot 8 \times 10^{-4}$ Pb^{204} and at the end of the irradiation this had decayed to $2 \cdot 5 \times 10^{-4}$ Pb^{204}. The radiogenic Tl^{205} is given by $Tl^{205*} = 2 \cdot 5 \times 10^{-4} Pb^{204} \exp(-\Delta t/3 \cdot 5 \times 10^7) = 3 \cdot 4 \times 10^{-3} Tl^{205} \exp(-\Delta t/3 \cdot 5 \times 10^7)$ and was observed to be not more than 0·01 Tl^{205} in the Canyon Diablo meteorite in which $Pb^{204}/Tl^{205} = 13 \cdot 5$. These data indicate that so little Pb^{205} was produced in the planetesimals that only one-third of the observational upper limit for Tl^{205*} is expected even if $\Delta t = 0$. Thus, much more precise measurements will be needed to employ Tl^{205*}/Pb^{204} as a measure of Δt. It is interesting to note that Anders and Stevens found an interval greater than 10^8 years between continuous galactic synthesis and the time at which Pb/Tl was finally established in Canyon Diablo and an interval greater than 3×10^8 years for the case of sudden synthesis. They used the abundances of Clayton & others who give $Pb^{205}/Pb^{204} = 4$ in each synthesizing event and $Pb^{205}/Pb^{204} = 0 \cdot 015$ at the end of galactic synthesis. It will be clear that the time interval $\geqslant 10^8$ years precludes any possibility of the Ag^{107} anomaly being due to Pd^{107} remaining at the end of synthesis in stars in the galaxy.

15. Anomalous isotopic abundances in the meteorites: The noble gases

Reynolds (1960 abcd) has observed anomalous values for the abundances of the isotopes of Xe in meteorites relative to that in the atmosphere of the Earth. Table 11 lists the isotopic composition of atmospheric Xe and the observed anomalies in the Richardton chondritic (stone) meteorite and the Murray carbonaceous chondrite. The anomalies are defined as:

$$\delta Xe^A = \frac{(Xe^A/Xe^{136})_{Met}}{(Xe^A/Xe^{136})_{Atmos}} - 1 \tag{45}$$

where δXe^A is essentially $(Xe^A{}_{Met} - Xe^A{}_{Atmos})/Xe^A{}_{Atmos}$ after allowance for differential fractionation of Xe relative to other elements has been made by reference to Xe^{136} taken as standard. Any fractionation is taken as the same for all isotopes of Xe. If atmospheric Xe abundances are taken to be primordial (see discussion below) then we can make the identification $\delta Xe^A = \Delta Xe^A/Xe^A$ where ΔXe^A corresponds to ΔN_A in equations (40), (41), and (42). We follow Reynolds in his choice of Xe^{136} as standard. Our reasons are that Xe^{136} is not a high yield spallation product, has "normal" abundance, is not produced by neutron capture by any stable nucleus and is itself not seriously depleted by neutron capture. Xe^{136} is produced abundantly in U^{235}-fission but the contribution from this source is found to be quite small.

Using the same techniques, Reynolds (1960 b) has failed to find anomalies in those isotopes of Kr on which measurements could be made. The experimental results are incorporated in Table 12. Moreover, Reynolds does not find anomalies in the meteoritic He, Ne, and A abundances which cannot be reasonably explained in terms of nuclear reactions induced by relatively recent cosmic ray bombardment of Richardton and Murray. Finally, he has established that Murray definitely contains primordial noble gases not due to cosmic ray bombardment nor to

Table 11

Isotopic Xe data

Isotope	124	126	128	129	130	131	132	134	136
Rel. atmos. abundance	·0010	·0009	·019	·263	·041	·213	·270	·105	·090
Richardton anomaly	·56	·42	·20	·51	·10	·06	·02	·02	= 0
Murray anomaly	·380	·355	·194	·100	·102	·068	·024	·009	= 0
Murray error (±)	·029	·060	·007	·005	·010	·005	·005	·005	
σ_A (barns)	74		< 5	45	< 5	120	0·2	0·2	0·2
n, γ-parent			I^{127}	Te^{128}	Xe^{129}	$TeXeBe^{130}$	Xe^{131}		
σ_{A-1} (barns)			5·6	·15	45	·23, < 5,10	120		
Calc. anomaly*	·20	≡ ·42	·20	—	·12	−·03	·03	·01	·01

* These calculations assume that all Xe irradiation products remain in the planetesimals and that only 5 per cent of primordial solar system Xe (relative to Si) was incorporated into the planetesimals. These assumptions may apply to Xe.

Table 12

Isotopic Kr data

Isotope	78	80	82	83	84	86
(N_A/N_{84}) atmos.	·00622	·040	·203	·203	≡ 1	·305
Richardton anomaly				·04 ± ·04	—	·04 ± ·01
Murray anomaly	·00 ± ·10	−·0073 ± ·023	−·0163 ± ·008	−·0094 ± ·007	—	·0052 ± ·008
σ_A (barns)	2·0	95	45	220	·16	·06
n, γ-parent		Br^{79}	Br^{81}	$KrSe^{82}$	Kr^{83}	
σ_{A-1} (barns)		10·4	3·1	45, 2·1	220	
Calc. anomaly*	·14	·34	·04	−·03	·01	0

* These calculations assume that all Kr irradiation products remain in the planetesimals and that only 5 per cent of primordial solar system Kr (relative to Si) was incorporated in the planetesimals. Clearly these assumptions do not apply to Krypton.

radioactive decay of K, U, or Th. It is also generally assumed that the terrestrial noble gases are largely primordial with the exception of A^{40} from the decay of K^{40} and He^4 and He^3 from direct and indirect effects of U and Th radioactivity.

It will be immediately clear that no simple explanation can be forthcoming for these observations on the noble gases in meteorites. In what follows we calculate the modification to primordial rare gas abundances arising from planetesimal irradiation characterized by the parameters $Y_s = 10^{-4}$, $n_r/\Sigma = 4 \times 10^{-3}$ and $F_d = 10$. These values have been found in the preceding sections of this paper to be relevant for terrestrial and meteoritic material. No evidence has come to our attention which requires that the material of the meteorites received different irradiation during the planetesimal stage.

Consider first the light noble gases HeNeA. Estimates are given in Table 7 for the overall irradiation yield, N_r, after dilution, for the various isotopes of these elements with the exception of A^{40}. These yields indicate the following ratios: $He^3/He^4 = 0{\cdot}18$, $Ne^{21}/Ne^{20} = 0{\cdot}33$ to $0{\cdot}50$, $Ne^{22}/Ne^{20} = 1{\cdot}1$, and $A^{36}/A^{38} = 15$. Ne^{21} may be depleted from its primary yield by $Ne^{21}(n, \alpha)O^{18}$ while A^{36} is augmented by $Cl^{35}(n, \gamma)Cl^{36}(\beta^- \nu^*)A^{36}$. These ratios are quite different than the atmospheric ratios $He^3/He^4 \approx 10^{-6}$, $Ne^{21}/Ne^{20} = 2{\cdot}8 \times 10^{-3}$, $Ne^{22}/Ne^{20} = 9{\cdot}7 \times 10^{-2}$, and $A^{36}/A^{38} = 5{\cdot}3$. Thus, either the spallation and neutron capture products escaped from the planetesimals or the primordial gases incorporated in the planetesimals exceeded by a considerable factor the overall irradiation yields. The latter alternative seems highly unlikely in view of the facts that the condensation and freezing points of HeNeA are well below the 130 to 200 °K temperature at which the planetesimals formed. Furthermore, it has already been pointed out in Section III, 8 and emphasized in the Appendix, that most of the He^3 produced must, of necessity, have escaped from the region of irradiation because of the extremely large $He^3(n, p)T^3$ cross section. It has been noted in Section III, 5 that this region was the outer layers of the planetesimals. This matter is discussed more fully in Section IV, 1 and there an attempt is made to explain the retention of some primordial noble gas at the same time that the irradiation products escaped and were removed along with other gases from the region of the inner planets.

We assume that the HeNeA irradiation products escaped both from the irradiated terrestrial material and from the irradiated meteoritic material. Thus the irradiation yields are irrelevant in regard to present terrestrial and meteroritic abundances. Morrison & Pine (1955) have shown that, in all probability, the terrestrial helium isotopes, He^4 and He^3 are of local radiogenic origin, the latter from secondary processes such as $Li^6(n, \alpha)T^3(\beta^- \nu^*)He^3$. Atmospheric Ne is very rare indeed compared to its presumed solar abundance. Particle streams from the Sun are capable of supplying the observed amount in a time short compared to the age of the Earth. The relative Ne isotope abundances are consistent with nucleosynthesis in the stars of the galaxy (as discussed in detail by B²FH 1957) and not with the yields of Table 7. If particle streams from the Sun are responsible for all the noble gases then some mechanism of fractionation favouring the retention of the heavier gases must have been in operation since the atmospheric abundance relative to solar abundance increases progressively by many orders of magnitude from Ne to Xe (Brown 1952). Primordial gases or solar effluents, the noble gases now in the atmosphere will be considered not to have been modified by the irradiation processes discussed in this paper. There is the possibility that atmospheric Xe has been modified by the fission of Pu^{244} as suggested by Kuroda (1960) and discussed below.

At this point, we turn to the anomalous Xe abundances found in meteorites by Reynolds which have been tabulated in Table 11. The Xe^{129} anomaly will be considered first. This anomaly has been attributed by Reynolds to the radioactive decay, $I^{129}(\beta^- \nu^*)Xe^{129}$, which has a mean lifetime, $\bar{\tau}_{129} = 2{\cdot}5 \times 10^7$ years. Moreover, Reynolds emphasized that the other anomalies were also outside of experimental error except perhaps for the very smallest ones ($< 0{\cdot}02$).

Reynolds's explanation for the Xe^{129} anomaly in meteorites assumes that when the I/Xe ratio was finally fixed in the meteoritic material some I^{129} remained from a nucleosynthesis which had occurred not too long before. The subsequent decay of the I^{129} and trapping of the resultant Xe^{129} yielded the anomaly. For a time Δt between the termination of nucleosynthesis and the final establishment of the ratio I/Xe in the meteoritic material, Reynolds wrote

$$\frac{Xe^{129*}}{I^{127}} = \left(\frac{I^{129}}{I^{127}}\right)_0 \exp(-\Delta t/\bar{\tau}_{129}) \tag{46}$$

where I^{127} is taken as a convenient standard as determined in the meteorite in question, Xe^{129*} is the amount of Xe^{129} attributed to the decay of I^{129} in the meteorite, and $(I^{129}/I^{127})_0$ is the ratio of I^{129} to I^{127} at the end of nucleosynthesis. Solving for Δt yields

$$\Delta t = 5{\cdot}7 \times 10^7 \left[\log \frac{I^{127}}{Xe^{129*}} + \log\left(\frac{I^{129}}{I^{127}}\right)_0\right]. \tag{46'}$$

By an ingenious combination of activation and mass spectrometric techniques Reynolds (1960 d) has been able to determine I^{127}/Xe^{129*} in meteorites. For Richardton, he finds discrepant results for two different samples but gives reasons for preferring one value $(I^{127}/Xe^{129*}) = 1{\cdot}02 \pm 0{\cdot}11 \times 10^5$ so that $\log(I^{127}/Xe^{129*}) = 5{\cdot}0$. For the meteorite Indarch he gives a preliminary value $\log(I^{127}/Xe^{129*}) = 4{\cdot}4$ and we have estimated from his results that for Murray, $\log(I^{127}/Xe^{129*}) \sim 4{\cdot}8$. In his original paper, Reynolds (1960 a) used a "sudden synthesis" model and assumed $(I^{129}/I^{127})_0 \sim 1$. At that time Reynolds estimated from his first results that $\log(I^{127}/Xe^{129*}) = 6{\cdot}1$ so that $\Delta t = 3{\cdot}5 \times 10^8$ years. The newer and more direct ratio given above for Richardton yields $\Delta t = 2{\cdot}8 \times 10^8$ years and slightly lower values for the other meteorites. Wasserburg, Fowler & Hoyle (1960) showed that on a continuous synthesis model $(I^{129}/I^{127})_0 = \bar{\tau}_{129}/T \sim 2{\cdot}5 \times 10^{-3}$ where $T \sim 10^{10}$ years is a rough estimate for the duration of nucleosynthesis in the galaxy prior to the formation of the solar condensation. The assumption was made that I^{129} and I^{127} are produced in equal abundance in each supernova explosion in which the iodine isotopes are principally produced. The analysis of Clayton & others (1961) indicates that the production ratio for I^{129} relative to I^{127} is probably closer to 2. Fowler & Hoyle (1960) find an effective duration for supernova synthesis in the galaxy before the formation of the solar system to be $9{\cdot}5 \times 10^9$ years. Fowler & Hoyle took into account both an evolutionary period and a subsequent decrease in activity for supernova events. With these estimates $(I^{129}/I^{127})_0 = 5 \times 10^{-3}$, $\log(I^{129}/I^{127})_0 = -2{\cdot}3$ so that for Richardton $\Delta t = 1{\cdot}5 \times 10^8$ years. There can be little question concerning the essential point made by Wasserburg, Fowler & Hoyle but $1{\cdot}5 \times 10^8$ years seems rather short for the interval between the end of galactic nucleosynthesis and the formation of large bodies in the solar system. If this interval was actually greater than 2×10^8 years as commonly thought, then $(I^{129}/I^{127})_0 < 10^{-3}$ and Reynolds's results are almost an order of magnitude greater than expected. Thus, we turn to synthesis of I^{129} in the planetesimals as an alternative explanation and assume that supernova produced I^{129} had decayed to a very low value before formation of large bodies in the solar system.

According to the discussion preceding the derivation of equation (40), I^{129} will be produced in the planetesimals by spallation primarily of nuclei in the range of mass numbers 130 to 148. This range includes isotopes of Xe(2·6), Cs(0·1), Ba(3·7), La(0·7), Ce(1·2), Pr(0·2), Nd(0·7) and Sm(0·3) where the numbers in brackets are the elemental abundances on the Si $= 10^6$ scale given by Clayton & others (1961). On the same scale, the authors give $I = I^{127} = 0{\cdot}2$. These abundances are taken as applying to primitive solar matter. For Nd and Sm, we have included the abundance only for the isotopes with $A \leqslant 148$. Reasons will be given subsequently for the belief that Xe was not incorporated in full abundance in the planetesimals so that Xe $= 2{\cdot}6$ is neglected in what follows. Thus, in Equation (40)

$$\sum_{A+1}^{A'} N_A = 6{\cdot}9.$$

When multiplied by $\gamma_I/(A'-A) = \gamma_I/19$ this becomes $0{\cdot}36\,\gamma_I$. Then with $Y_s/F_d \approx 10^{-5}$, $A^{\ddagger} \approx 25$, and the original amount of I^{129} taken as zero, we find from equation (40) that the total amount of I^{129} produced by spallation in the planetesimals is $9 \times 10^{-5}\,\gamma_I$. It is difficult to estimate γ_I for I^{129} which is neutron rich rather than neutron deficient but it will be considerably less than unity and probably not much greater than 0·1 so that the spallation yield of I^{129} can be rounded off to 10^{-5}. I^{129} is also produced by neutron capture in Te^{128} which has a thermal neutron capture cross section of 0·15 barns and an abundance according to Clayton & others (1960) given by 0·6. Neglecting self-depletion, equation (41″) thus gives a contribution equal to $3{\cdot}6 \times 10^{-5}$ to the I^{129} production in the planetesimals, making a total equal to $4{\cdot}6 \times 10^{-5}$ Decay of the I^{129} during the production leads to a value for the abundance of I^{129} at the end of planetesimal synthesis given by $I_0{}^{129} = 4 \times 10^{-5}$. Te^{126} has a thermal neutron capture cross section of 0·8 barns and an abundance equal to 0·3. I^{127} has a capture cross section of 7·0 barns and spallation yields are small compared to "normal" abundances. Thus $I^{127} \approx 0{\cdot}2$ was not appreciably changed during irradiation in the planetesimals and $(I^{129}/I^{127})_0 = 2 \times 10^{-4}$ at the end of the synthesis or $\log(I^{129}/I^{127})_0 = -3{\cdot}7$. With this value one finds $\Delta t = 75 \times 10^6$, 40×10^6, and $\sim 60 \times 10^6$ years for Richardton, Indarch, and Murray respectively. These intervals are, in general, about one order of magnitude greater than the interval found in Section III, 12 for the incorporation of Al^{26} in the parent bodies of meteorites and the interval found in Section III, 14 for the final establishment of the Pd/Ag ratio in such bodies. It does not seem unreasonable at all that the interval required to establish the final ratio I/Xe should have been longer than these other intervals. Degassing of Xe and other noble gases may well have continued until the final stages of the formation of the meteoritic parent bodies. A time scale summary is given in Table 13 for the intervals involving the radioactive decay of Al^{26}, Pd^{107}, I^{129} and Pb^{205} which have been under discussion. Sudden and continuous nucleosynthesis in the Galaxy as well as nucleosynthesis in planetesimals in the solar nebula are treated. The short time scales indicated and the internal consistency of the intervals definitely point towards synthesis in the solar nebula as a "last minute" supplement to the general process of galactic nucleosynthesis. Essentially the same chronology as that depicted here has been independently suggested and just published by Anders (1961) without the details of the early solar system which we have presented.

In the discussion to this point the implicit assumption has been made that terrestrial Xe^{129} received *no* contribution from the decay of I^{129}. Quantitatively a 10 per cent contribution cannot be excluded. This is to say that atmospheric Xe^{129} may have an anomaly relative to primordial Xe^{129} given by 0·1 and that the Murray and Richardton anomalies relative to primordial Xe^{129} are 0·2 and 0·6 using the data of Table 11. For sake of argument, assume that terrestrial igneous rocks have the same isotopic Xe composition as the atmosphere. For Murray, Reynolds gives Xe = $4 \cdot 3 \times 10^{-8}$ cc STP/g while for igneous rocks Brown (1952)

Table 13

Time scale summary (yr)

	Galactic Nucleosynthesis Sudden	Galactic Nucleosynthesis Continuous	Nucleosynthesis in the Solar Nebula
Heating effects Al^{26}($1 \cdot 0 \times 10^6$ yr)†	6×10^6	$Al^{26} \sim 0$	10^6
Ag^{107*}(2%)‡ from Pd^{107} ($1 \cdot 0 \times 10^7$ yr)	$6 \cdot 5 \times 10^7$	$Pd^{107} \sim 0$	10^7
Xe^{129*}(42%) from I^{129} ($2 \cdot 5 \times 10^7$ yr)	$2 \cdot 8 \times 10^8$	$1 \cdot 5 \times 10^8$	6×10^7
Tl^{205*}(< 1%) from Pb^{205}($3 \cdot 5 \times 10^9$ yr)	$\geqslant 3 \times 10^8$	$\geqslant 10^8$	$Pb^{205} \sim 0$

† Mean lifetimes are given in brackets.
‡ Per cent anomalies are given in brackets.

estimates Xe = $3 \cdot 4 \times 10^{-10}$ cm³ STP/g. For the Murray meteorite, Goles & Anders (1960) find I = $2 \cdot 3 \times 10^{-7}$ g/g while Rankama & Sahama (1950) give I = 3×10^{-7} g/g for igneous rocks. Thus I/Xe in terrestrial rock exceeds that in Murray by a factor ~ 170. If the anomaly in terrestrial Xe is one-half that in Murray then an overall factor of ~ 340 is involved. This can be compensated for by assuming that I/Xe was fixed in crustal rocks of the Earth approximately 6 mean lives of I^{129} or 150×10^6 years after it was established in Murray material. If it is assumed that atmospheric Xe was originally incorporated in the crustal rocks, then Brown's figure must be increased to $\sim 7 \times 10^{-9}$ cm³ STP/g and the interval just referred to is reduced to 75×10^6 years. It does not seem unreasonable that I/Xe was established in the Earth's crust later than in the parent bodies of the meteorites which are customarily assumed to have been considerably smaller than the Earth.

The anomalous abundances of isotopes of Xe, other than Xe^{129}, found by Reynolds in Murray, Richardton, and other meteorites cannot be explained by fractionation of Xe relative to some long-lived radioactive nucleus such as I^{129}. These anomalies are to be contrasted with the "normal" abundance of the Kr isotopes listed in Table 12 and the "normal" abundances of HeNeA previously discussed. Kuroda (1960) has made the attractive suggestion that the anomaly in each of the "unshielded" isotopes Xe^{131}, Xe^{132}, Xe^{134}, and Xe^{136} is really an excess in the atmospheric abundance arising from the spontaneous fission of Pu^{244}($\bar{\tau} \approx 10^8$ years). He takes Xe^{130} as a standard because it is shielded by Te^{130} in fission decay and finds substantial "negative" anomalies for the "unshielded" isotopes and smaller "positive" ones for the shielded isotopes. His calculations are based on a sudden synthesis model in which he assumed $Pu^{244} \sim U^{238}$ at the end of nucleosynthesis. In a continuous synthesis model $Pu^{244} \sim 0.02\, U^{238}$ if the effective production interval is 10^{10} years and Kuroda's calculated anomalies are considerably reduced so that the quantitative agreement with observation is marginal. However, overall quantitative agreement can be obtained by reducing the formation time for the Earth from the end of nucleosynthesis to one mean lifetime for Pu^{244} or 10^8 years. There is the additional difficulty emphasized by Kuroda that the Xe^{132} anomaly is several times that observed for the other unshielded isotopes and it will remain for observations on the mass spectrum of the fission products of Pu^{244} to clarify this point. Kuroda does not discuss the small anomalies for the "shielded" isotopes.

We are inclined to consider Kuroda's suggestion a satisfactory one but wish to propose an alternative and very tentative explanation along the general line under discussion in this paper for the Xe anomalies in addition to that for Xe^{129} already discussed.* An alternative to Kuroda's explanation will be necessary if it is established that the interval from the end of galactic synthesis to fairly complete formation of the Earth requires several Pu^{244} mean lifetimes. Pu^{244} is not produced in planetesimal synthesis. In the analysis to this point, no evidence has been found for a different intensity of irradiation for primitive meteoritic material relative to that for primitive terrestrial material. Thus the simplest explanation of the situation from the point of view of this paper would seem to be that HeNeAKr irradiation products escaped from the planetesimals while, in the case of Xe, the irradiation products escaped from the planetesimals which formed the Earth but not from those which formed the parent body or bodies of the meteorites. The lower temperatures in the region of formation of the pre-meteoritic planetesimals may have resulted in these bodies retaining Xe either as trapped atoms or as hydrate (see Section IV, 1).

It will be clear that it is necessary to calculate the changes in isotopic Xe and Kr abundances relative to primordial values due to the planetesimal irradiation. A comparison of these results with the observations then leads to a quantitative estimate of what fraction of the Kr and Xe irradiation products were retained in the planetesimals. Some of the necessary data and the results are given in Tables 11 and 12. Comments on the calculations follow.

Xe^{126}: This isotope is produced only by spallation, not by neutron capture. The spallation yield is quite similar to that calculated for I^{129}, namely $9 \times 10^{-5} \gamma_I$. In this case we estimate $\gamma_I \approx 0.6$. Clayton & others (1961) give Xe = 2.6 so $Xe^{126} = 0.0024$ in primitive solar system material. Thus $\Delta Xe^{126}/Xe^{126} = 2.2$ per cent if Xe was not fractionated relative to neighbouring elements in the formation of the planetesimals. In view of the properties of noble gases, this would hardly seem reasonable. Even if primary and secondary Xe were retained in the planetesimals once they were formed, this does not necessarily mean that all Xe was incorporated in the planetesimals during formation. Let p equal the factor by which Xe is decreased relative to neighbouring elements in forming the planetesimals. Then $\Delta Xe^{126}/Xe^{126} = 2.2\, p$ per cent. If we identify this with $\delta Xe^{126} = 42$ per cent for the Richardton meteorite, then $p \approx 20$. This is to say that 5 per cent of primordial Xe relative to other elements was incorporated in the planetesimals. This value for p has been used in calculations on the other isotopes. Table 11 compares the

* Since the preparation of this paper, Krummenacher & others (1961) have suggested that the anomalies are due to excess meteoritic fission xenon and to gross mass fractionation of terrestrial xenon.

observed and calculated anomalies. The large value for p justifies the omission of the Xe abundance in calculating the spallation yield of I^{129}.

Xe^{124}: Only spallation contributes as for Xe^{126}, but in this case the value of γ_I is much less certain. A reasonable estimate would be $\gamma_I \sim \frac{1}{3}$ but this yields only about one-half of the observed anomaly.

Xe^{128}: Spallation, with $\gamma_I \approx 1$ almost certain, yields a 2 per cent increase which is small compared to the increment from neutron capture in I^{127}. For this increment, using $Xe^{128} = 0{\cdot}019$ Xe $= 0{\cdot}05$, we have

$$\frac{\Delta Xe^{129}}{Xe^{128}} = p\frac{I_{127}}{Xe^{128}}\frac{\sigma_{127}n_r}{F_d\Sigma} = 20\times\frac{0{\cdot}2}{0{\cdot}05}\times 5{\cdot}6\times 4\times 10^{-4} = 18 \text{ per cent.} \tag{47}$$

The self-depletion by neutron capture is less than 0·2 per cent so the total increment is 20 per cent in good agreement with observation.

Xe^{130}: This isotope has a fairly large abundance and in unaffected by spallation. The self-depletion is negligible but neutron capture in Xe^{129} is important. The quantity p does not enter into the calculation and one finds $\Delta Xe^{130}/Xe^{130} = 12$ per cent in good agreement with observation.

Xe^{131}: In this case the major effect is self-depletion by neutron capture for which $\Delta Xe^{131}/Xe^{131} = 0{\cdot}1[1-\exp(-120\times 4\times 10^{-3})] = -3{\cdot}8$ per cent. Spallation and neutron capture in Te^{130} Ba^{130} Xe^{130} add small increments but only change this result to $\Delta Xe^{131}/Xe^{131} = -3$ per cent. This definitely disagrees with the observed *positive* anomalies of 6 and 6·8 per cent. It will be observed, however, that the sign of the anomalies does depend on the choice of the "standard" isotope.

Xe^{132}: This isotope is increased by the large neutron capture in Xe^{131} so that $\Delta Xe^{132}/Xe^{132} = (Xe^{131}/Xe^{132})\times 3{\cdot}8$ per cent $= 3$ per cent in fair agreement with the observations.

Xe^{134} and Xe^{136}: Spallation and neutron capture processes in the planetesimals did not change the abundances of these isotopes appreciably. Neutron induced fission in U^{235} makes a small contribution. U^{235} has a large total neutron absorption curve of which 85 per cent is due to fission. The fission yield for Xe^{134} and Xe^{136} is slightly over 6 per cent so $\Delta Xe^{134} \sim \Delta Xe^{136} \sim 0{\cdot}05$ $\Delta U^{235} \sim 0{\cdot}005$ U^{235}. Fowler & Hoyle (1960) give $U^{235} = 0{\cdot}067$ on the Si $= 10^6$ scale at the time of formation of the solar system. Clayton & others (1961) indicate that all r-process abundances such as that of U^{235} must be multiplied by 0·4 so that $U^{235} = 0{\cdot}027$ and $\Delta Xe^{134} \sim \Delta Xe^{136} \sim 1{\cdot}4\times 10^{-4}$. Both Xe^{134} and Xe^{136} constitute about 0·1 Xe $= 0{\cdot}26$ so that with $p = 20$, the expected anomalies are given by $\Delta Xe^{134}/Xe^{134} \sim Xe^{136}/Xe^{136} \sim 1{\cdot}4\times 10^{-4}\times 20/0{\cdot}26 \sim 1$ per cent. Since Xe^{136} has been taken as a standard, 1 per cent should be subtracted from the other calculated anomalies except in the case of Xe^{134}. The observations on Xe^{134} may indicate a small positive anomaly which is not accounted for on the basis of the calculations made here. In accord with the motivation for these calculations, the effects of Pu^{244}-fission have been neglected in discussing Xe^{131} to Xe^{136}.

It will be clear from the above discussion that the observed and calculated anomalies are in rough quantitative agreement. Qualitatively, the arguments given reduce to the following: (a) abundant Xe^{129} was enriched by the decay of I^{129}; (b) the rare isotopes Xe^{124} and Xe^{126} were enriched by spallation; (c) the next rarest isotopes Xe^{128} and Xe^{130} were enriched by neutron capture in I^{127} and Xe^{129} respectively; (d) only small anomalies (<10 per cent) are to be expected in the remaining isotopes. These remarks should be compared with line 3 of Table 11, or better still, with the observations as graphically displayed in Figure 1 of Reynolds (1960b). However, there are several small discrepancies and it will require additional observations on isotopic abundances in meteorites to lead to a full understanding of the Xe anomalies. Again, it is to be noted that Kuroda's suggestion may prove to be a satisfactory one, in which case it need only be argued that Xe irradiation products escaped from the planetesimals along with those of the other noble gases.

Recently, Zähringer & Gentner (1961) found no variation in the Xe^{124}/Xe^{132} ratio on heating the meteorite Abee over the temperature range 700° to 1350 °C. They were led by this finding to suggest that Xe^{129} is not due to decay of extinct I^{129} *in situ* but that Xe^{129} was already mixed with Xe^{132} at the time of formation of the meteorite and thus cannot be differentiated from the primordial xenon in a heating experiment. Jeffrey & Reynolds (1961) have repeated the experiment with different results and "see no particular need to doubt that the Xe^{129} was formed from I^{129} decay *in situ*". Our analysis has been made on the basis of the point of view of Jeffrey and Reynolds. On the other hand, if Zähringer and Gentner are proven to be correct, then it might be suggested that the I^{129} decay took place in the planetesimals and that thorough mixing of the Xe-isotopes took place on formation of the parent bodies of the meteorites. A complete recalculation of the I/Xe ratio in the planetesimal material which eventually formed the meteorites will be necessary in this case.

Calculations have also been made to ascertain what Kr anomalies would result if Kr irradiation products were retained in the planetesimals. The results of the calculations are given in Table 12; the measurements are due to Reynolds (1960b, 1961).

Kr^{78}: Spallation yields for Kr^{78} come primarily from mass numbers up to $Z = 90$. The contributing elements and their abundances in brackets are Rb(4·3), Sr(17·7), Y(11·4), and Zr^{90}(20·9). The spallation increment with $\gamma_I \sim \frac{1}{2}$ is thus $4{\cdot}2 \times 10^{-4}$. The abundances are Kr = 18, $Kr^{78} = 0{\cdot}06$ so that $\Delta Kr^{78}/Kr^{78} = 0{\cdot}7p$ per cent. It would seem reasonable that p for Kr exceeded $p = 20$ for Xe, so 14 per cent is a minimum estimate for $\Delta Kr^{78}/Kr^{78}$. The minimum value does not greatly exceed the 10 per cent uncertainty in Reynolds observation on Murray.

$Kr^{82}Kr^{83}Kr^{84}Kr^{86}$: Only small changes are expected as a result of planetesimal irradiation for these isotopes. Reynolds employs Kr^{84} as a comparison standard.

Kr^{80}: This isotope receives a large increment from neutron capture in Br^{79}. Using the abundances $Br^{79} = 2{\cdot}1$ and $Kr^{80} = 0{\cdot}4$ in equation (41′) we find

$$\frac{\Delta Kr^{80}}{Kr^{80}} = 0{\cdot}1\left[\frac{10{\cdot}4}{95} \times \frac{2{\cdot}1}{0{\cdot}4} \times 20 - 1\right][1 - \exp(-95 \times 4 \times 10^{-3})] = 34 \text{ per cent.} \tag{48}$$

Again the use of $p = 20$ yields a minimum value. Reynolds (1961) finds at most a 2·3 per cent anomaly in Kr^{80} if one uses the error in his measurement recorded in Table 12. This seems to be conclusive evidence that the Kr irradiation products were not retained in significant amount in the planetesimals.

PART IV. FURTHER ASTROPHYSICAL CONSIDERATIONS

1. An intermediate stage in the formation of the solar system

The question now arises as to how far the nuclear considerations of Part III may be taken as determining the manner of origin of the terrestrial planets.

First, it has been found that DLiBeB were formed by spallation and neutron irradiation in conditions of hydrogen deficiency. The calculated deficiency relative to solar abundances is a factor of about 4×10^3. Such a situation not only yields the correct relative abundances of Li^6, Li^7, Be^9, B^{10}, B^{11}, but also, as a by-product, explains the origin of terrestrial deuterium, with a D/H abundance ratio equal to $1 \cdot 5 \times 10^{-4}$. The conclusion seems unavoidable:

That the material of the terrestrial planets was irradiated by high-energy particles from the Sun, at a stage of development when the material had become very largely, but not completely, separated from hydrogen.

Next, it will be noticed that the requirement for the high-energy solar particles to be absorbed in the planetary material with appreciable efficiency sets an upper limit to the size of the bodies in which the material was condensed; clearly the greater the size, the smaller the probability of an energetic particle being absorbed. If the bodies were of planetary dimensions the probability would be very small indeed.

For simplicity, suppose all the planetesimals to be spheres of radius a. Let there be N such spheres and let their average internal mass density be ρ g cm^{-3}. Then the total mass M_T of the terrestrial planets is given by

$$M_T \approx \frac{4\pi}{3} \rho a^3 N. \tag{49}$$

If a high-energy solar particle were to pass through the planetesimals along a straight line at angle θ to the plane of the solar system, the probability of the particle striking one of the planetesimals would be of order

$$P \approx 1 - \exp(-\pi a^2 N/A \sin\theta), \tag{50}$$

where A is a ring-shaped area on the plane of the solar system contained between circles of radii r_1 and r_2 ($r_1 > r_2$). The values of r_1 and r_2 are to be chosen such that the bulk of the matter lies at distances from the Sun $> r_2$ and $< r_1$. The quantity $\pi a^2 N$ is the total area of projection of all the planetesimals taken on the plane of the solar system.

Substituting for $\pi a^2 N$ from the above formula for M_T, and writing $A = \pi(r_1^2 - r_2^2)$ the probability of the proton striking one of the planetesimals is of order

$$P \approx 1 - \exp(-3M_T/4\pi\rho a \sin\theta[r_1^2 - r_2^2]). \tag{51}$$

The main uncertainty in the exponent lies in the $\sin\theta$ factor. In order of magnitude, it would seem reasonable to take θ to be equal to the ratio of the width of the planetary disk to the radius. At the temperatures existing in the gas, we expect this ratio to be $\sim 1:10$. For a planetesimal possessing the chemical composition arrived at in Section III, 8 the density $\rho \approx 1 \cdot 8$ g cm^{-3}. For the terrestrial planets we take r_1 to be the radius of the Earth's orbit and we take r_2 to be the radius of the orbit of Venus; in which case $r_1^2 - r_2^2 \approx 10^{26}$ cm^2. The present total mass of the terrestrial planets $\approx 1{\cdot}2 \times 10^{28}$ g. Probably the original mass was somewhat greater than this, say $M_T \approx 1{\cdot}5 \times 10^{28}$ g. With these values, and with a measured in metres, the probability of a solar proton striking one of the planetesimals is of order

$$P \approx 1 - \exp(-2/a). \tag{52}$$

The probability is thus of order unity, provided a is not greater than a few metres. The general order of magnitude of this result can hardly be affected by the uncertainities involved in the calculation. The above formula tends to underestimate the probability of collision, since the incident high-speed particles were assumed to move through the distribution of planetesimals along a straight line. In fact, a charged particle must spiral along a magnetic line of force, and the spiralling motion clearly increases the effective path length. Probably a could be as high as 10 to 20 m before the probability of collision began to fall appreciably below unity. Equation (52) yields $P \approx 10$ per cent for $a = 20$ m. This conservative value has been employed in the calculations on energy requirements in Section III, 9.

At this stage, we recall the consideration of Section II, 1 that the icy planetesimals of metric dimensions were left behind by the outflowing gas. Coagulation to metric dimensions caused the planetesimals to fall out of the hydrogen and helium gas that had hitherto swept them along. Hence, the astrophysical considerations require hydrogen deficiency to arise when $a \gtrsim 1$ m. It is satisfactory that this requirement can be met without the probability of collision of the solar high-energy particles falling too low.

A further interesting relation between the astrophysical and the nuclear considerations arises from the nuclear requirement that not all the planetary material be irradiated by the solar particles; otherwise, all nuclei with extremely high thermal neutron cross sections, such as Gd^{157} and U^{235}, would be entirely scoured out. The dilution factor obtained in Section III, 5 was ≈ 10.

The condition that there be a dilution factor sets a *lower limit* to the size of the planetesimals. While it is true that at any particular moment some planetesimals will shield others from the solar particle flux, we find it difficult to believe that nine-tenths of the bodies could have remained closely shielded *over a time-scale as long as* 10^7 *years*. Collisions between the planetesimals, together with their orbital motions around the Sun (which prevent the planetesimals remaining permanently above or below the plane of the solar system), must lead to a constant reshuffling in the relative positions of these bodies. The shuffling of the planetesimals due to eccentric and inclined orbits and due to collisions also suggests that meteoritic and terrestrial matter received the same irradiation in the intermediate stage as seems to be the case. Hence, we feel that every single body must receive irradiation by high-energy particles and certainly we expect the majority of them must do so. In this case, the only way to preserve nuclei such as Gd^{157} and U^{235} is for the bodies to be large enough in diameter for the solar particles, predominantly protons, to fail to penetrate throughout their interiors. The material of each individual planetesimal must not be uniformly irradiated. The mean free path for protons discussed in Section III, 9 will be used in the subsequent calculations.

A proton of energy > 330 MeV penetrates on the average about 72 g cm^2 of material before interacting. For material composed of ice and silicates in roughly equal weight the density is about $1{\cdot}8$ g cm^{-3}. Hence the path length of the solar protons in the material is about 40 cm. Thus the depth of penetration into the planetesimals is $\delta a = 40$ cm. The condition that the mass of the shielded interior of a body of radius a be ten times the mass of the exposed surface skin of thickness δa gives

$$\tfrac{4}{3}\pi a^3 \approx 10(4\pi a^2 \delta a) \tag{53}$$

$$a \approx 30\delta a \approx 12 \text{ m.} \tag{54}$$

It will be apparent that many other solutions of this problem are possible. The typical distribution of radii found in asteroids, meteorites, meteors and interstellar dust is one in which the mass contributed by successive intervals in radii is nearly constant. If this rule applies to the planetesimals then the proton path length of 40 cm is compatible with planetesimals ranging from 1 to 50 m in radius.

A distribution in planetesimal sizes permits an explanation of the possibility discussed in Section III, 15 that the noble gas irradiation products, with the possible exception of Xe, escaped from the planetesimals while some primordial noble gas was clearly retained. Particle streams from the Sun may be the source of atmospheric noble gases (although this is unlikely) but it is hardly possible to make the same explanation for the primordial noble gases incorporated in Murray. On the other hand, it does not seem unreasonable that a few, large planetesimals retained in their interiors the small amount of noble gas necessary to account for both meteoritic and atmospheric abundances while the great majority of the planetesimals lost all noble gases. In regard to the possible retention of Xe irradiation products in the pre-meteoritic planetesimals, it is necessary, of course, to assume some segregation of these planetesimals from the pre-terrestrial ones at least during the later stages of the irradiation. Segregation in orbits at a greater distance from the Sun and thus at lower temperature may have served to lead to some retention of Xe but not of HeNeAKr. The fact that Reynolds (1960b) finds total Xe/Kr = 1·6 in Murray while total Xe/Kr = 0·08 in the atmosphere is very suggestive in this regard. In fact, Reynolds's results yield $\mathrm{Ne_{Mur}/Ne_{Atmos}} = 70$, $\mathrm{A_{Mur}}^{36,38}/\mathrm{A_{Atmos}}^{36,38} = 36$, $\mathrm{Kr_{Mur}/Kr_{Atmos}} = 40$ while $\mathrm{Xe_{Mur}/Xe_{Atmos}} = 800$ on a reasonable adjustment of atmospheric abundances to the standard Si = 10^6 scale. The Xe ratio is clearly an order of magnitude greater than the others. Preferential retention of the Xe primordial component may well be accompanied by preferential retention of the Xe irradiation products.

The two nuclear arguments, that the efficiency of absorption of solar particles be not very small and that there be a dilution factor of order 10, yield lower and upper limits to the dimensions of the condensed planetesimals. Both limits are of the same general order, of the order of 10 metres. This is precisely of the order demanded by the astrophysical model set out in Section II, 1. Hence, the nuclear considerations relating to the origin of DLiBeB are closely consistent with our astrophysical model of the origin of the planetary system.

While it would probably be overstating the case to assert that the nuclear considerations entirely prove the correctness of the astrophysical model, we believe the nuclear considerations provide a severe constraint that any satisfactory alternative model must satisfy. There is a very strong requirement that the material of the terrestrial planets became very largely separated from hydrogen at a stage where the material was condensed into bodies of metric dimensions.

This requirement serves to cast considerable doubt on theories in which the terrestrial planets evolved from very much larger proto-planets in which hydrogen was present in the normal solar proportion and on the idea that the Earth itself ever had a strongly reducing atmosphere predominantly composed of hydrogen.

The present argument has certain biological implications. Conditions during the formation of the planetesimals were highly favourable to the building of biologically interesting molecules. At that stage, H_2O, NH_3, CH_4 were present in high concentrations in the surrounding medium. Free hydrogen was overwhelmingly abundant and fine solid particles presented a large surface area in which absorption processes could take place. Electromagnetic activity on the solar surface supplied energy of order 10^{45} ergs in the form of ultraviolet light over the interval of 10^7 years. In contrast to this biologically favourable situation, conditions seem to have become much less favourable after the separation of the solid planetesimals from the gaseous component. Thereafter, oxidizing conditions appear to have replaced the former reducing conditions. These remarks apply to the subsequent formation of the Earth from the metric planetesimals. The possibility is suggested that pre-biotic or even biotic materials could have been formed in the planetesimals before the formation of the Earth. This speculation will not be elaborated at this time.

Note added in proof. Recent evidence for the existence of complex organic compounds in carbon-containing meteorites has been given by Briggs (1961). Briggs suggests that the compounds "are the decomposition products of an extra-terrestrial life form or they are abiotic compounds formed early in the development of the solar system".

2. Later history of the planetesimals and time-scale problems

We have not made any definite time sequence which leads from the stage of great solar activity to that of a quiescent Sun and a planetary system with present abundance ratios. As the Sun approaches its ultimate luminosity, long before reaching the main sequence, the icy matrix containing silicates, iron and the spallation products is subject to heating, at 1 AU, which will evaporate the H_2O, NH_4OH and most of the noble gases. Considering the time-scale for the heating up of the Sun to be 3×10^7 years, it is important to note that considerable evidence exists for a surprisingly rapid condensation of solids in the region where the meteorites formed (or the parent body from which they came). It can be argued that a supernova event triggered the condensation of the solar system or that the Sun originated in an "association" of stars such as those young stars which seem to be moving radially outward from a common point. Discontinuing these interesting speculations, the evidence involving radioactive decays such as Al^{26}, Pd^{107} and I^{129} suggests that the parent body condensed from the irradiated planetesimals in a period between 10^6 and 10^7 years. This parent body was a planetoid of considerable size in which a core and mantle were differentiated (e.g. Pd was separated from Ag). Differentiation and loss of noble gases ended in less than 10^8 years. *The short time-scale is a problem of formation of solid bodies and their chemical differentiation. The problem of an excessively short interval between nucleosynthesis in stars and the formation of the meteorites no longer exists.*

There exists a wide range of possible sequences of events. For example, the parent bodies of meteorites might have already formed during the irradiation process or they might have started to condense after it stopped and before the icy planetesimals were melted. Thus, especially at a distance of several AU from the Sun, it is not certain that the ices melted and evaporated before or after planetesimals aggregated into larger bodies. The relative concentration of water and solids during the formation of larger bodies may eventually be estimated from the composition of the Moon, asteriods, carbonaceous chondrites, and other samples differing in essential features from the Earth. In one case, Xe isotopes might be retained in anomalous abundances by the pre-meteoritic planetesimals as suggested in Section III, 15. Another factor, different for the meteorite-formation zone is its proximity to the major-planet zone. In the latter, the larger densities of H and He will have reduced the peculiar velocities in the pre-meteorite belt, and also tied down the magnetic lines of force which guide the solar particles back into the ecliptic plane. Furthermore, initial peculiar velocities were smaller than near the Earth by $1/r^{\frac{1}{2}}$, approximately 40 per cent, or 80 per cent in collisional energy. If condensation of large meteoritic-parent-bodies proceeded too rapidly, however, only a negligible surface irradiation would have occurred. The time table is very uncertain, but it may be suggested that meteoritic material was irradiated in the form of icy planetesimals, and that larger bodies were formed by accretion, without melting, very rapidly before radioactive sources such as Al^{26} had decayed. Water and the noble gases leaked out with rates dependent on obscure chemical processes holding them in the crystal lattice.

The timetable for the terrestrial planets is also short, and their higher black-sphere temperature during early stages of planetesimal accretion makes the question even more critical. If the ices and other volatile compounds were lost when the metric planetesimals melted, subsequent accretion had to occur in a low-density gaseous zone. Only when the planet was sufficiently large could gravitational capture, for example, of Ne, A, Kr and Xe occur. On the other hand, hydrated Mg, Si, Fe compounds largely retained their H_2O, which became available, when pressures or temperatures rose, for oxidation or reduction of terrestrial minerals. Thus, gravitational and chemical differentiation would dominate in planet composition if the icy planetesimals melted, and be less significant if they survived till accretion began. The isotope ratios computed in the Section III, 15 would be unaffected by the fate of the ices and even the relative abundances of the elements, except for chemically inactive gases, notably N, He, Ne, Kr, Xe. These should provide very important insight into the fate of the early-stage planetesimals. Of course, a combination of both hypotheses is also possible; if some very large planetesimals existed, they would provide nuclei for gravitational condensation of the terrestrial planets, have negligible irradiation (i.e. have cosmic isotope ratios), and capture the evaporated, irradiated gases of smaller bodies. It will be clear that only additional observational evidence on meteorites can lead to a solution of these ambiguities in our knowledge of the early history of the solar system.

PART V. SUMMARY OF CONCLUSIONS

The concentration by mass of hydrogen in the terrestrial planets is less than the concentration in solar material by a factor of approximately 10^7. Hence, if the planets were derived from solar material, there must have been a process in which hydrogen became very largely separated from the planetary material. The suggestion that the terrestrial planets are the residues of massive protoplanets of solar chemical composition is shown in this paper to be incorrect. Hydrogen did not escape from protoplanets (and thereafter from the solar system), but from the material of the terrestrial planets when the latter existed as a multitude of small planetesimals of metric dimensions.

These conclusions are derived from the remarkable fact that in the Earth, the ratio of the stable isotopes of the element lithium, $Li^6/Li^7 = 0{\cdot}08$, is small compared to unity as also is the ratio of the stable isotopes of the element boron, $B^{10}/B^{11} = 0{\cdot}23$. It has long been realized that severe difficulties stand in the way of any theory of the origin of lithium and boron as well as of beryllium, Be^9, and of deuterons, D^2. DLiBeB are rapidly destroyed in hydrogen burning in stellar interiors even granting that they are produced at all; their production does not lie in the main line of element synthesis. The low abundance of these light nuclei attests to this. It has been realized, as a consequence, that the synthesis must almost certainly occur through spallation by high-energy, non-thermal particles interacting with relatively cool, moderate density material irrespective of the detailed astrophysical environment in which it takes place. In this paper it is suggested that the high-energy particles, mainly protons, became accelerated through electromagnetic activity at the surface of the primeval Sun. The relevant spallation occurred, on the other hand, in an intermediate stage for planetary material after the material had become separated from the Sun but before formation of the planets. The active period lasted for approximately 10^7 years just before the young Sun settled on to the main sequence.

Recent astronomical studies of the abundance of Li in young T Tauri stars, and of Be in peculiar A stars, serves as the basic observational evidence for this point of view. These studies show, for example, that at least ten times more Li per gram of material is observed in the surfaces of T Tauri stars than in the surrounding nebular material from which these stars presumably formed. High abundance of Li and Be in stars is assumed strongly correlated with high-energy particle activity and the appearance of recognizable T Tauri-like spectral features although the T Tauri stars have not yet been shown to possess large magnetic fields. It follows that young, active stars produce light nuclei sufficient unto themselves but not sufficient to produce detectable abundances in representative galactic material.

Spallation reactions give lithium and boron isotope ratios of order unity. Thus the observed ratios appear to demand thermal neutrons. The thermal cross sections for the reactions $Li^6(n, \alpha)T^3$ and $B^{10}(n, \alpha)Li^7$ are exceptionally large. There is thus a depletion of Li^6B^{10} and an augmentation of Li^7 when free neutrons are present. The existence of neutrons occasions no surprise in itself, for the spallation reactions themselves produce neutrons. Over the period of irradiation, the neutron flux approximated $10^7\ n/\mathrm{cm}^2\,\mathrm{s}$. The total number of neutrons relative to the total absorption cross section of the material irradiated was

$$n_r / \sum_A \sigma_A N_A = 4 \times 10^{-3}.$$

The time integrated neutron flux was $4 \times 10^{21}\ n/\mathrm{cm}^2$.

Neutron reactions on Li^6B^{10} cannot occur with appreciable probability in material of solar composition, since in such material effectively all free neutrons are captured by hydrogen. The neutron reactions on Li^6B^{10} must therefore have occurred both after the planetary material became separated from the Sun and after the excess hydrogen concentration had become separated from the planetary material. The time of flight from the Sun is too long compared to the half-life of free neutron decay for the neutrons in question to have originated at the solar surface. The necessity for thermalization of the neutrons requires that the (n, α) reactions did not occur with the planetary material in a gaseous phase at low density.

Appropriate physical conditions are satisfied by solid planetesimals of metric dimensions with H_2O and oxides of MgSiFe in the ratio two-to-one by volume. The hydrogen present in the planetesimals is found from independent nuclear considerations to have been almost an order of magnitude greater than the silicon abundance and in fact even slightly greater than the oxygen abundance. H_2O probably occurred both as ice and as hydrate. Before the onset of hydrogen burning, the primeval Sun was much less luminous than the present Sun. The temperature of the planetary material near the Earth fell in the range 130° to 200 °K. H_2O condensed and froze in the planetesimals but not NH_3 nor CH_4. Thermalization of the neutrons was promoted by "elastic" scattering in the hydrogen. The neutrons not only produced the required lithium and boron ratios, but neutrons captured by protons gave sufficient deuterons to produce ten times the terrestrial D/H ratio in the material irradiated.

Not all the planetary material was irradiated by high-energy solar protons, otherwise all nuclei with very large thermal neutron cross sections, such as Gd^{157}, would have been entirely scoured out. Gd^{157} is observed to have approximately "normal" abundance in terrestrial gadolinium. From the D/H data, it is estimated that only 10 per cent of the material received irradiation. It is suggested that this 10 per cent constituted the surface layer of the solid planetesimals, the interior material of these bodies being shielded from the solar protons by the surface layer. This suggestion requires the planetesimals to possess radii of the order of 10 m.

This result agrees with the requirement that the planetesimals present an adequate target area to the solar protons. Total area relative to volume and mass decreases with increasing size; quantitatively, radii no more than the order of 10 m as an upper limit are required. The results also agree with a model for the origin of the planetary system in which a magnetic torque coupling existed between the Sun and the gaseous component of the planetary material. The torque coupling transmitted angular momentum from the Sun to the weakly ionized gaseous component, causing the gas to move slowly outwards. The outward motion separated the gas from all solids of adequate size that were condensed out of the gaseous phase. It is satisfactory that the condition for the gas to separate from the solids is that the latter possess at least metric dimensions. Otherwise the planetesimals were removed by the gas. From all points of view, the mean radii of the remaining planetesimals, which were irradiated after the exodus of the shielding gas, approximated 10 m. A uniform mass distribution over the range 1 to 50 m is permitted.

Several by-products of the main argument appear. A deduction is made of the relative abundances of $Li^6:Li^7:Be^9:B^{10}:B^{11} = 0{\cdot}17:0{\cdot}17:0{\cdot}12:0{\cdot}42:0{\cdot}12$, as produced by spallation. The result is shown to be in satisfactory agreement with cosmic ray data on the relative abundances of $Li:Be:B = 0{\cdot}35:0{\cdot}22:0{\cdot}43$. In addition, it is shown that terrestrial C^{13} and N^{15} may have been produced in the planetesimal stage.

Conditions during the formation of the planetesimals were highly favourable to the building of biologically interesting molecules. The possibility is suggested that pre-biotic or even biotic materials could have been formed in the planetesimals before the formation of the Earth.

The terrestrial–meteoritic abundances of DLiBeB determine the intensity and extent of the spallation and neutron processes in the planetesimals. Using the irradiation parameters so determined, a calculation has been made for anomalous abundances to be expected in meteorites due to fractionation processes in the parent bodies of these objects. In particular, the production of radioactive nuclei in the planetesimals, such as Pd^{107} and I^{129}, leads to an explanation of radiogenic Ag^{107} and Xe^{129} which have been found as anomalies in meteorites having high Pd/Ag and I/Xe ratios. The intervals between the last event or events of nucleosynthesis and the end of fractionation processes in meteoritic materials are found to fall in the range 10^6 and 10^8 years. These relatively short intervals definitely indicate that spallation and neutron processes in the planetesimals were a "last minute" supplement to the general processes of nucleosynthesis in the stars of the Galaxy.

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APPENDIX: ADDITIONAL NUCLEAR CONSIDERATIONS

In this appendix, we treat other possibilities for the synthesis of LiBeB with the observed isotopic abundances. It is, of course, possible to argue that the observed abundances correspond to the relative production rates in some unknown primary process without the neutron irradiation postulated in this paper. We have been unable to discover a primary process which would produce $Li^6 \sim 0{\cdot}1\ Li^7$ and $B^{10} \sim 0{\cdot}2\ B^{11}$ as observed. In what follows, we will take $Li_s^6 \sim Li_s^7$ and $B_s^{10} \sim B_s^{11}$ where the subscript s designates abundances resulting from the primary production process by spallation or otherwise. We will assume that neutron irradiation reduced Li^6 and B^{10} and increased Li^7 through (n, α) reactions. The necessity for the rapid escape of He^3 from the irradiated layers of the planetesimals is also discussed and a generalization of equations (40) and (41) is derived.

1. Survival of B^{10} as Be^{10}

In Part III of the main body of this paper, the production time was assumed to be long compared to the half-life of Be^{10}, $2{\cdot}7 \times 10^6$ years. As an alternative, consider the case when the production time is short compared to this lifetime. Then equation (14) of Part III must be written

$$B^{10} = B_s^{10}\left(\frac{\Sigma}{\sigma_{10}n_r}\right)\left[1 - \exp\left(-\frac{\sigma_{10}n_r}{\Sigma}\right)\right] + Be_s^{10}, \tag{A1}$$

$$\approx B_s^{10}\left(\frac{\Sigma}{\sigma_{10}n_r}\right) + Be_s^{10}, \tag{A1$'$}$$

where $Be_s^{10} = \alpha_{10}'\,n$ is the number of mass 10 nuclei produced directly as Be^{10} and $B_s^{10} = \alpha_{10}\,n$ is the number produced directly as B^{10} and C^{10}. The Be^{10} nuclei survive the neutron irradiation and eventually decay to B^{10}. The half-life of the

C^{10} is so short, 10 s, that the C^{10} decays during the primary production to B^{10}. It is also necessary to rewrite equation (18) as

$$Li^7 = Li_s^7 + B_s^{10} - (B^{10} - Be_s^{10}). \tag{A2}$$

Then equation (21) can be rederived and is found to have the modified form

$$\frac{n_r}{\Sigma} = \frac{I_7 + I_{10}(B/Li)}{\sigma_6 I_6(\alpha_7/\alpha_6) + \sigma_{10} I_{10}\gamma_{10}(B/Li)} \tag{A3}$$

$$= \frac{0{\cdot}972}{70 + 176\gamma_{10}} \tag{A3'}$$

where

$$\gamma_{10} = \frac{1 + (\alpha_{10}'/\alpha_{10})}{1 + \sigma_{10}(n_r/\Sigma)(\alpha_{10}'/\alpha_{10})} \tag{A4}$$

and the other symbols have the same meaning as in the main text. In the numerical evaluation of n_r/Σ we have used $\alpha_7/\alpha_6 = 1$ and $B/Li = 0{\cdot}24$ as before. For $\alpha_{10}' = 0$, $\gamma_{10} = 1$ we obtain $n_r/\Sigma = 4 \times 10^{-3}$ as before.

The case of synthesis short in duration relative to the life-time of Be^{10} requires an estimate of α_{10}'/α_{10}, the ratio of the direct production of Be^{10} to that of B^{10} and C^{10}. On the basis of the charge independence of nuclear forces, Be^{10} and C^{10} ought to be produced in about equal numbers in spallation, while on the basis of its greater stability and high spin ground state, B^{10} ought to outnumber both Be^{10} and C^{10}. Thus, we take $\alpha_{10}'/\alpha_{10} \sim 1/5$. Then $\gamma_{10} = 1{\cdot}20/(1 + 770\, n_r/\Sigma)$. Substitution of this value into equations (A4) and (A3') yields $n \cdot/\Sigma = 10 \times 10^{-3}$ which is again well within an order of magnitude of the value $n_r/\Sigma = 4 \times 10^{-3}$ found for the duration of synthesis long compared to the lifetime of Be^{10}. That the synthesis is long in this respect is indicated by our best estimate of the solar contraction time, but in any case we see that the results are not extremely sensitive to the duration of the synthesis just as they are not sensitive to the choice of α_7/α_6 or B/Li as emphasized in Part III. In addition we find $Li_s^6 : Li_s^7 : Be_s^9 : B_s^{10} : Be_s^{10} : B_s^{11} =$ 73:73:20:20:4:20. The large Li spallation rates do not seem as reasonable as those found in the case treated in the main body of this paper. However, this case permits $B_s^{10} \sim B_s^{11}$ and this may prove to be true when appropriate experimental evidence becomes available.

The large Li spallation ratio indicated at the end of the last paragraph follows directly from the use of $B/Li = 0{\cdot}24$ or $Li/B = 4{\cdot}2$ from Goldschmidt's analysis of meteoritic abundances. It can be argued that the B/Li ratio is not established with high accuracy and that it would be preferable to use the primary spallation ratios indicated by the cosmic ray abundances discussed in Section III, 6. After correction of the Li observations by a factor of 1·67 these ratios, indicate $Li_s : Be_s : B_s = 0{\cdot}35 : 0{\cdot}22 : 0{\cdot}43$ as indicated in Table 6. A somewhat larger experimental correction for the Li would have yielded $Li_s : Be_s : B_s \sim 0{\cdot}4 : 0{\cdot}2 : 0{\cdot}4$ or 2:1:2. These ratios are just in proportion to the number of stable isotopes and would imply roughly equal production at each mass number, i.e. $Li_s^6 \sim Li_s^7 \sim Be_s^9 \sim B_s^{10} \sim B_s^{11} \sim 20$, the numerical value, 20, being given by the $Be^9 = Be\ a$ and $B^{11} = Be_s''$ abundances on the $Si = 10^6$ scale. If we assume that B^{10} has survived primarily as Be^{10}, then n_r/Σ can be found quite simply. First of all equation (A2) yields $Li^7 = Li_s^7 + B_s^{10} \sim 40$. Then Li^6 becomes $\sim 40 \times 7{\cdot}4/92{\cdot}6 = 3{\cdot}2$ and equation (12′) of Section III, 3 yields

$$\frac{n_r}{\Sigma} \approx \frac{1}{\sigma_6}\frac{Li_s^6}{Li^6} \sim \frac{20}{945 \times 3{\cdot}2} = 6{\cdot}6 \times 10^{-3}. \quad (A5)$$

This value is very close to the value $n_r/\Sigma = 4 \times 10^{-3}$ used in the calculations of this paper. Experimental measurements on spallation yields of LiBeB will be required before n_r/Σ can be determined with greater accuracy.

2. Neutron irradiation subsequent to primary production

Neutron irradiation simultaneous with production has been assumed in Part III. Neutron irradiation subsequent to primary production must be considered as a possible alternative. Let LiBeB be produced and then a fraction β be irradiated by neutrons. Let the neutrons reduce the Li^6 irradiated by e^{-x} where $x = (n_r/\Sigma)\sigma^6$. Then B^{10} will be reduced by e^{-4x} since $\sigma_{10} \approx 4\sigma_6$. It is then possible to write

$$Li^6 = 7{\cdot}4 = Li_s^6(1-\beta+\beta e^{-x}) \quad (A6)$$

$$B^{10} = 4{\cdot}5 = B_s^{10}(1-\beta+\beta e^{-4x}) + Be_s^{10} \quad (A7)$$

$$Li^7 = 92{\cdot}6 = Li_s^7 + B_s^{10} - (B^{10} - Be_s^{10}) \quad (A8)$$

$$B^{11} = 19{\cdot}5 = B_s^{11}. \quad (A9)$$

If B^{10} survives almost entirely as Be_s^{10}, then it will be clear that $\beta \sim 1$ and e^{-4x} must be very small. The quantity e^{-x} can be found as Li^6/Li_s^6 and the result for n_r/Σ will be very similar to what we have already found in Part III. Let us then consider that the neutron irradiation occurs after all the primary Be^{10} has decayed so that Be_s^{10} can be set equal to zero in (A7) and (A8) and B_s^{10} should include the primary Be^{10} production. Under this assumption, it will be noted that the B^{10} then survives principally in the material not irradiated. In the part irradiated, $(B^{10}/B_s^{10}) = (Li^6/Li_s^6)^4$ so that any reasonable reduction for Li^6, say by $\frac{1}{4}$, reduces B^{10} to a very small value, $\frac{1}{256}$ in our example. The analysis in Part III is unaffected by this difficulty since the equilibrium abundances in simultaneous irradiation depend inversely, not exponentially, on the cross sections.

Assume then, that e^{-4x} is small enough to be neglected but retain e^{-x}. Then manipulation of (A6) to (A9) yields

$$1-\beta = 0{\cdot}23 B_s^{11}/B_s^{10} \leqslant 0{\cdot}23 \quad (A10)$$

$$1-\beta(1-e^{-x}) = \frac{0{\cdot}38 Li_s^7/Li_s^6}{4{\cdot}98 - B_s^{10}/B_s^{11}} \approx \frac{0{\cdot}38}{4{\cdot}98 - B_s^{10}/B_s^{11}}. \quad (A11)$$

Equations (A10) and (A11) yield $1{\cdot}9 < B_s^{10}/B_s^{11} < 4{\cdot}6$ which is a reasonable range for B_s^{10}/B_s^{11}. The median value $B_s^{10}/B_s^{11} = 2{\cdot}8$ is very close to what we found in Part III and yields $\beta = 0{\cdot}92$, $x = 2{\cdot}3$ and $n_r/\Sigma = 2{\cdot}4 \times 10^{-3}$. This last value is also very close to the value determined previously in Part III.

If the setting for primary production followed by neutron irradiation is the early solar system, then the conclusions of the main body of this paper are changed very little. However, an additional *ad hoc* assumption must be made, namely that part of the LiBeB produced was not subject to neutron irradiation. We prefer simultaneous production and neutron irradiation then because it is simpler and, of course, follows straightforwardly if spallation is the overall process.

If the production of LiBeB occurred before the formation of the solar system, then either for subsequent or simultaneous neutron irradiation, we see that the hydrogen abundance during the irradiation must be intermediate between the solar and terrestrial values. This is because n_r/Σ is the same order of magnitude in the two cases. It may well be that LiBeB were produced in stellar or interstellar circumstances where the heavy elements were largely separated from hydrogen and then subsequently mixed with large amounts of hydrogen. We would then be left with no explanation for the D^2/H^1 ratio. In any case, we find it most natural to place the circumstances in the planetary material early in the formation of the solar system.

3. Necessity for rapid escape of He^3 from the planetesimals

The nucleus He^3 is produced in fairly substantial amounts in the direct spallation processes and also as the ultimate product in $Li^6(n, \alpha)T^3(\beta^- \nu^*)He^3$. Table 7 indicates that the overall production amounts to about one He^3 per 11 neutrons produced. Thus the effective value of α_3 is 0·09. He^3 has a very large cross section, $\sigma_3 = 5500$ barns, for the $He^3(n, p)T^3(\beta^- \nu)He^3$ reaction. In the neutron flux, $10^7 n/\text{cm}^2\,\text{s}$, previously found, He^3 has a mean lifetime of 6×10^4 years. The mean lifetime for T^3 decay is 18 years so mass 3 material is He^3 most of the time and He^3 acts as a catalyst in processing neutrons into protons. It thus could have a catastrophic effect on the neutron budget necessary for the production of D^2 and the depletion of Li^6 and B^{10}.

Since the He^3 production is proportional to the neutron production, once Li^6 reaches equilibrium, we can treat this problem and similar ones by generalizing equations (11) (13) (15) and (25) to include a term in Σ which is linear in n. Let

$$\Sigma = \Sigma \sigma_A N_A = (1+\gamma n)\Sigma_0 \qquad \text{(A12)}$$

where γ is a constant of proportionality and Σ_0 replaces the original Σ. For He^3 we have a contribution $\gamma\Sigma_0 = \alpha_3\sigma_3 = +500$. For substances which are depleted during the irradiation process, the quantity γ will be negative. If now we set $f_r = 1$, equation (11) becomes

$$\frac{d\text{Li}^6}{dn} = \alpha_6 - \frac{\sigma_6 \text{Li}^6}{(1+\gamma n)\Sigma_0}. \qquad \text{(A13)}$$

The ultimate solution, for $\text{Li}^6 = 0$ when $n = 0$, is found to be

$$\text{Li}^6 = \text{Li}_s^6 \frac{\Sigma_0/\sigma_6 n}{1+\gamma\Sigma_0/\sigma_6}[\gamma n + 1 - (\{1+\gamma n\}^{1/\gamma n})^{-\sigma_6 n/\Sigma_0}] \qquad \text{(A14)}$$

where n is now the terminal value for the neutron variable.

For small $\gamma n < 1$, we have $\{1+\gamma n\}^{1/\gamma n} = e$ and equation (A14) reduces to equation (12), Section III, 3. For large γn

$$\text{Li}^6 = \frac{\text{Li}_s^6}{1+\sigma_6/\gamma\Sigma_0}. \qquad \text{(A15)}$$

For a given $\gamma\Sigma_0$ it will be clear that Li^6 will be reduced more and more relative to Li_s^6 as γn or n/Σ_0 is increased. Thus the minimum $\text{Li}^6/\text{Li}_s^6$ or maximum $\text{Li}_s^6/\text{Li}^6$ is given by equation (A15). Numerically, $\sigma_6/\gamma\Sigma_0 = 945/500 = 1{\cdot}9$ so that $\text{Li}_s^6 <$ 2·9 $\text{Li}^6 = 21{\cdot}5$. For B^{10}, we have $\sigma_{10}/\gamma\Sigma_0 = 3\,870/500 = 7{\cdot}7$ so that $B_s^{10} < 8{\cdot}7$

$B^{10} = 39{\cdot}2$. We have assumed $Li_s^7 = Li_s^6$ so $Li_s^7+B_s^{10} < 60{\cdot}7$. But $Li_s+B_s^{10}$ must equal $Li^7+B^{10} = 97{\cdot}1$ so we see that $\gamma\Sigma_0 = \alpha_3\sigma_3 = 500$ will not yield a possible solution even assuming a very large flux in order to make Li_s^6/Li^6 and B_s^{10}/B^{10} as large as possible. *The neutrons interact with He³ if it remains in the planetesimals.* Thus we assume that He³ escapes from the *surface layers* of the planetesimals, where it is produced, in an interval short compared to 6×10^4 years and very short compared to the total irradiation time of 10^7 years. Not more than 10 per cent of the He³ produced can be retained. This is not at all unreasonable in view of the size, composition, and temperature of the planetesimals. This matter is discussed in greater detail in Section III, 15.

4. General expression for combined spallation, neutron capture and beta-decay

Generalizing the notation of Section III, 13, the rate of change of abundance $N_{A,Z}$ for a nucleus of mass number A and charge number Z is given as a function of the running neutron variable $n_r'(0 < n_r' < n_r)$ by

$$\frac{dN_{A,Z}}{dn_r'} = -\frac{a}{n_r}N_{A,Z}+\frac{1}{n_r}b(n_r') \tag{A16}$$

where

$$a = \frac{\sigma_{A,Z}n_r}{\Sigma}+Y_sA^{\frac{1}{2}}+\frac{T}{\bar{\tau}_{A,Z}}$$

$$b(n_r') = \frac{\sigma_{A-1,Z}n_r}{\Sigma}N_{A-1,Z}(n_r')+Y_sA^{\frac{1}{2}}\left(\frac{\gamma_1}{A'-A}\right)\sum_{A+1,Z}^{A',Z'}N_{A,Z}(n_r')+ + \frac{T}{\bar{\tau}_{A,Z-1}}N_{A,Z-1}(n_r').$$

The first terms in a and b represent neutron interactions, the second terms represent spallation effects and the third terms represent negative beta-decay. The third terms are strictly correct only if n_r' varies uniformly in time over the total irradiation interval designated by $T(0 < t < T)$. The appropriate mean lifetimes for negative beta decay are designated by $\bar{\tau}_{A,Z}$ and $\bar{\tau}_{A,Z-1}$. In the second term, Z' represents the charge number of stable nuclei with mass number $A' \approx 1{\cdot}15\,A$.

Integrating and solving for $\Delta N_{A,Z}$ in $F_d\Delta N_{A,Z} = N_{A,Z}(n_r)-N_{A,Z}(0)$ and with $N_{A,Z} \equiv N_{A,Z}(0)$, one finds

$$\Delta N_{A,Z} = -\frac{N_{A,Z}}{F_d}[1-\exp(-a)]+\frac{\exp(-a)}{F_d}\int_0^1 b(n_r')\exp(an_r'/n_r)\,dn_r'/n_r \tag{A17}$$

$$\approx \frac{1}{F_d}\left[N_{A,Z}-\frac{b}{a}\right][1-\exp(-a)] \quad \text{for} \quad b(n_r') \approx b(0) \equiv b. \tag{A17'}$$

Equation (A17) must be employed rather than the sum of equations (40) and (41″) when the conditions $Y_s < 1$ and $\sigma_A n_r/\Sigma < 1$ are not satisfied.

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